G.4

Comments?
Bill Morgan

TIROS CONSTELLATION MISSION STUDY (1994 - 2004)

DRAFT

September 30, 1994

This study assesses the past reliability performance of the Television/Infrared Observation Satellites (TIROS) and predicts the future ability of the TIROS constellation to provide environmental monitoring services

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EXECUTIVE SUMMARY

A Monte Carlo simulation model was created and used to assess the ability of the Television/Infrared Observation Satellites (TIROS) constellation to provide environmental monitoring from 1994 through 2004. The expected availability of the TIROS constellation was found to remain above 90%, for having both an AM and PM satellite, from now through 2001. An additional satellite will need to be ready for launch at that time in order to maintain the overall availability of the constellation. Several what-if exercises were studied to account for uncertainty in the input values used to arrive at these conclusions. In general, the conclusions did not change regardless of what reasonable input values were used. Also from these what-if exercises, it was determined that the baseline input values produced a conservative estimate of constellation performance. Of course, actual performance will not follow any of the plots generated in this study. In actuality, the satellites will either be available or not at any given time. The results of this study are average values based on hundreds of possible outcomes produced using identical operating rules and input values.

Success for the TIROS constellation required maintaining a TIROS satellite in each of two polar orbits, referred to as the AM and PM orbits. Satellites were replaced on demand due to either orbital drift or failure of a critical component or instrument. If replacement was due to orbital drift, then the old satellite was still considered available to provide temporary backup coverage for the new satellite should it fail. The model considered such things as the satellite production schedule, satellite reliability, launch vehicle reliability, and response time needed to launch a replacement satellite. Some of this information was defined by consensus with project personnel and other information was derived from past performance. Details concerning the derivation of satellite and launch vehicle reliability are provided in the appendices to this report

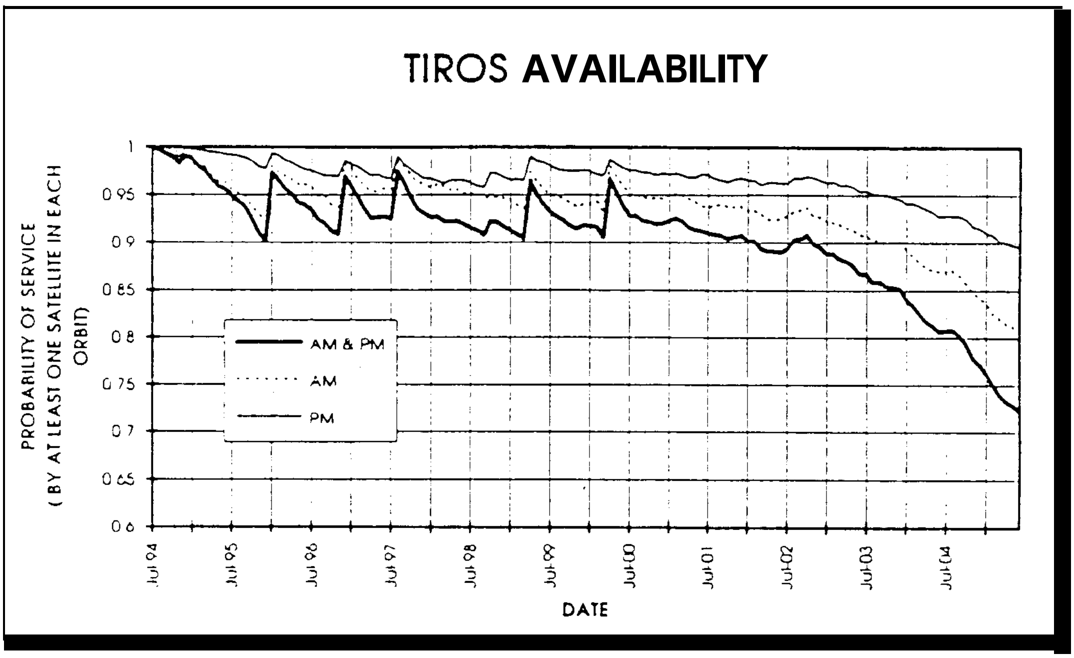
Each run of the Monte Carlo model randomly generated 200 possible scenarios of what might happen under the given operating rules and input data. These scenarios are then analyzed using traditional statistical methods to define what is most likely to happen. Baseline performance was defined by running the model ten times (i.e., 2000 scenarios) with the baseline input data The model's repeatability was also assessed from these ten runs and confidence intervals were generated. Next, several of the input values were modified, one at a time, and the model was run to assess sensitivity to that change. The results from each modified run were compared to the baseline confidence intervals to determine if the change results differed significantly from the baseline performance.

The model produced two types of outputs. First was a tabular summary showing mean values for various performance measures such as how much time the constellation should be expected to exist in a given state. The second type of output was graphical. Availability graphs show the probability that the constellation will exist in a given state on any given date. Reliability graphs show the probability that the constellation will have existed in a given state without interruption from the beginning of the simulation through some given date. This report generally focuses on the availability plots resulting from

each run. It is important to keep in mind that performance within a single scenario is usually a binomial function (i.e., go/no-go) for most of the measures cited in this study. The model outputs are continuous functions since they are the average of hundreds of scenarios. Thus, model outputs should usually be interpreted as probabilities of occurrence rather than as a degree of performance. For example, a satellite will either be available or not be available on some date. If availability of one-satellite coverage is reported as 90% on that date then there is a 90% probability that one-satellite service will exist on that date not that 90% of a satellite will be available.

Baseline results, both tabular and graphical, are shown below.

PERFORMANCE MEASURE	MEAN
Continuous coverage by ONE or more AM satellites	79 months
Continuous coverage by TWO AM satellites	26 months
Continuous coverage by ONE or more PM satellites	106 months
Continuous coverage by TWO PM satellites	36 months
Average time with NO AM satellite	8.4 months
Average time with ONE AM satellite	82 months
Average time with TWO AM satellites	41 months
Average time with NO PM satellite	4.4 months
Average time with ONE PM satellite	50 months
Average time with TWO PM satellites	78 months
Average number of AM outages	1.2
Average duration of an AM outage	6.8 months
Average number of PM outages	0.56
Average duration of a PM outage	7.9 months



The sharp vertical rises in the availability plots coincide with the production schedule delivery dates for new satellites. The magnitude of each rise is primarily a function of the launch vehicle reliability. In general, the PM orbit performs better than the AM orbit This is partially because the PM orbit (with its regular replacement intervals due to orbital drift) tends to have newer satellites than the AM orbit (with replacement only after failure). Also, the PM orbit is more likely to have a fully functioning on-orbit backup although it has probably drifted out of specification. These two facts produce a more shallow slope on the PM plots. The AM performance could be improved up to the level of PM performance by scheduling regular replacement intervals; however, the supply of replacement satellites would be consumed more rapidly.

Currently, the baseline data shows that an additional satellite (e.g., NOAA-O) is needed by the end of 2001 to maintain performance to the levels of the 1990's. This need date can be extended by about a year if PM orbit drift can be extended out to 5 years especially for the later launches. Such a situation may likely occur since NOAA-N and -N' are scheduled to launch on a new version of the Delta which is advertised to yield smaller insertion errors. Also, the need date for the next satellites can be extended if the mean lives of the TIROS satellites is actually better than the baseline data suggests. Again, this may well be the case since our experience with all GSFC satellites has shown that as the quantity of lifetime data increases then so do our mean life estimates.

The constellation's performance is driven by the failure model for each satellite. The drift life of the PM orbit is generally not a factor in the steady-state performance of the constellation since the satellites have only a 50/50 chance of surviving 4.5 years after launch.

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TIROS CONSTELLATION MISSION STUDY

1. INTRODUCTION. A Monte Carlo simulation model was created and used to assess the future ability of the Television/Infrared Observation Satellites (TIROS) constellation to provide environmental monitoring by the TIROS series of satellites. The impact of changes to the input data was also assessed. This data included, among other things, the satellite production schedule, satellite reliability, launch vehicle reliability, and response time needed in the event of a spacecraft failure. Some of this data was available, some was assumed, and some required further analysis. Included in the appendices are a launch vehicle reliability study performed previously by this office and a new TIROS reliability study.

2. GROUNDRULES, ASSUMPTIONS, AND DEFINITIONS.

A. Critical instruments on all TIROS satellites include AVHRR, HIRS, and AMSU (MSU and SSU up through NOAA-J). The PM satellite also includes SBUV.

B. The useful life of a satellite is limited by drift from the preferred nodal crossing time. The AM spacecraft does not drift significantly and thus, AM spacecraft drift is ignored in this analysis. Nodal crossing time for the PM spacecraft is 13:00 to 15:30. The time required to drift outside of this window depends primarily on launch vehicle performance. Typically, the PM satellites operate for 3-5 years inside this window. This study uses 4 years as the useful life limit and model sensitivity to this parameter is assessed.

C The TIROS-J satellite will launch on a 30-year-old Atlas-E rocket The K, L, and M satellites will launch on 20-year-old Titan II rockets. The N and N' satellites will be launched on the latest version of the Delta rocket_ All launch vehicles will be at least as good as the Atlas in supporting the orbital parameter specifications of altitude, inclination. and nodal crossing tune. Based on a study conducted last year of launch vehicle performance (see Appendix A), the Atlas/Centaur is expected to launch successfully 87.6% of the time, Titan III and IV rockets have an expected 88.7% success rate, and Delta's expected success rate is 96.3%. These success rates are based on the last 20 years of flight history.

D. If either an active spacecraft or launch fails, the replacement is launched after a 120-day (3 month) call-up delay accounting for preparation of a launch vehicle, removal of the replacement spacecraft from storage, and preparation of this spacecraft for launch. Of course, if a new spacecraft should become available from the manufacturer during this expected delay period then the delay would be shortened since this new spacecraft would not require as much preparation as one coming out of storage. A 200-day call-up delay is also evaluated.

E. Satellite failure is defined as the loss of any bus or instrument function which destroys the ability of the satellite to perform its primary objectives. Loss of redundant or non-critical functions does not constitute satellite failure. We recently updated our March 1993 statistical study of TIROS spacecraft reliability (see Appendix B). Both the data and our analysis techniques have changed since that study was originally conducted. In summary, the TIROS spacecraft data follows a three parameter Weibull curve having a Beta = 1.6, scale = 6.6 years, and t0 = -0.8 years. In layman's terms, these parameters imply that TIROS spacecraft have a characteristic life (36.8% probability of surviving) of 6.6 years although they have experienced 0.8 years of this time prior to launch and, they exhibit at increasing probability for failure as they age. This compares to the entire GSFC spacecraft experience which shows a constant probability for failure throughout their life with a characteristic life of 11.2 years.

F. Continuous service is required throughout the entire 1 l-year study period.

G. Spacecraft have full capabilities when launched (i.e., no failed hardware is launched).

H. Each spacecraft exists in only one of the following states at any particular time. These states are listed in the normal order of progression through a spacecraft's life cycle.

NEW — New spacecraft are those which have not been built and, those which are built and being stored until needed.

SCHED — Scheduled spacecraft have future launch dates assigned. These dates can be input to the model based on project schedules or, the dar [illegible] be assigned by the model in response to failures and consumable depletion.

LAUNCHED — Launched spacecraft have been launched and are undergoing on-orbit check-out_ They are not considered ACTIVE at that time but their presence is considered when scheduling a new launch to replace another spacecraft which fails during this check-out period.

ACTIVE — Active spacecraft are fully operational and used to meet the primary mission objectives.

BACKUP — Normally backup spacecraft are not fully capable and are not currently being used to meet any primary mission objective. Spacecraft are downgraded from ACTIVE to BACKUP after a failure or after drifting beyond a predetermined nodal crossing time. They usually continue to perform secondary objectives. They may be [illegible] at any time to ACTIVE status if necessary to cover any gaps between failure of another spacecraft and the launch/check-out of its replacement_

DISPOSED — Disposed spacecraft are no longer usable due to either failure or orbit drift.

I. Replacement spacecraft are launched in response to failures and to relieve satellites which are drifting outside their nodal crossing time window.

J. Older spacecraft are downgraded to backup status after being replaced such that no more than the required number of spacecraft are active at any time. These backup satellites can provide some (probably degraded) capability, in the event that the active satellite fails, while a replacement satellite is being prepared.

K. Depletion of fuel or other consumables are normally considered as a maximum life limit The TIROS satellites do not have any such constraints.

L. One AM and one PM spacecraft are required at all tunes. They are identical except for instrumentation. However, they cannot be moved to the opposite orbit once launched.

M. The current ground system can handle only four satellites. The oldest backup satellite will normally be turned off to meet this constraint- However, at least one satellite will be maintained in each orbit.

N. The input data needed is shown in Table 1. This input data is defined as follows:

Mission Length	Mission length is the overall data collection period being studied, measured in months.
Total # of S/C	The total number of spacecraft included in the study There must be a line of input data for each spacecraft in the study.
# of Active S/C	The number of active spacecraft is the number of spacecraft maintained on-orbit at any point in time to accomplish the primary objectives, i.e. the desired size of the constellation. This number must be no greater than the total number of spacecraft
# of Req'd S/C	The number of required spacecraft is the minimum number of spacecraft maintained on-orbit at any point in time to accomplish the primary objectives, i.e. the minimum size of the constellation. This number must be no greater than the number of active spacecraft. If the number of required spacecraft is less than the number of active spacecraft, the additional active spacecraft are treated as "hot spares".
S/C	S/C is any name, up to 8 characters, used to identify each particular spacecraft

TABLE 1
TIROS INPUT DATA

TIROS SIMULATION DATA

SIMULATION LENGTH = 132 MONTHS
TOTAL # of s/c = 10
# of ACTIVE S/C = 2
# of REQ'D S/C = 2

S/C	AM/ PM	AVAIL DATE	LAUNCH DATE	WEIBULL SCALE	WEIBULL SHAPE	LAUNCH Ps	LAUNCH DELAY	START DELAY	DRIFT LIFE	MAX LIFE
NOAA-9	PM	na	12/84	6.6	1.6	1.00	na	na	48	240
OPERATING AS A BACKUP TO NOAA-11										
NOAA-10	AM	na	9/87	6.6	1.6	1.00	na	na	240	240
OPERATING AS A BACKUP TO NOAA-12										
NOAA-11	PM	na	9/88	6.6	1.6	1.00	na	na	48	240
NOAA-12	AM	na	5/91	6.6	1.6	1.00	na	na	240	240
NOAA-J	PM	12/94	12/94	6.6	1.6	0.88	4	2	48	240
NOAA-K	tbd	1/96	1/96	6.6	1.6	0.89	4	2	tbd	240
NOAA-L	tbd	12/96	tbd	6.6	1.6	0.89	4	2	tbd	240
NOAA-M	tbd	8/97	tbd	6.6	1.6	0.89	4	2	tbd	240
NOAA-N	tbd	12/99	tbd	6.6	1.6	0.96	4	2	tbd	240
NOAA-N'	tbd	12/00	tbd	6.6	1.6	0.96	4	2	tbd	240

na = not applicable   tbd = to be determined by the model

AM/PM The AM/PM field designates whether a particular satellite is only usable for the AM or PM orbits. If left blank then the satellite will be launched where it is needed at the time since new satellites are designed to be used in either orbit After launch, this field will be used to record the orbit used.

Avail Date The available date for each spacecraft is the earliest date at which manufacturing and testing is complete and the spacecraft could be launched or placed in storage.

Launch Date	The launch date is the planned launch date for each spacecraft A launch date of zero indicates to the model that no firm schedule exists and it should launch that spacecraft whenever needed. Of course, a non-zero launch date must be no earlier than the available date. Also, the program will always launch a spacecraft on or before its non-zero launch date.
Weibull Scale	The Weibull scale factor represents the location on the distribution where only 36.8% of identical satellites remain active. It is commonly called the characteristic life, measured in years.
Weibull Shape	The Weibull shape factor (beta) is a indication of how the failure rate changes as the spacecraft ages. A unity shape factor indicates a constant failure rate. A shape factor greater than one indicates an increasing failure rate accounting for wearout and loss of redundant components. A shape factor less than one indicates a decreasing failure rate accounting for bum-in phenomenon.
Launch Ps	The probability of success fdr the launch of each spacecraft must be between 0 and 1. Typically launch vehicles have exhibited 70-95% success over the long run based on recent study of expendable launch vehicle (ELV) reliability.
Launch Delay	The launch delay time, measured in months, is the time required between identifying the need to launch a spacecraft and actually launching. This delay accounts for such activities as call-up and preparation of the launch vehicle and launch site, removal of the spacecraft from storage, final inspection and testing of the spacecraft, and integrating the spacecraft with the launch vehicle. The launch delay must be a positive an integer.
Start Delay	The start-up delay time, measured in months, accounts for the on-orbit check-out and calibration required to ready the spacecraft for active service following its launch. The start-up delay must be a positive integer.
Drift Life	The drift life, measured in months, of each spacecraft is the expected replacement interval. If replacement spacecraft are to be launched only after a failure rather than at planned intervals. then the drift life should be the same as the maximum life. The drift life must be a positive integer.
Max Life	The maximum spacecraft life, measured in months, is the life possible due to the limited supply of fuel or other consumables required to accomplish the primary objectives. The maximum life must be a positive integer. TIROS satellites have no consumables

constraint so this parameter is set to its maximum value to prevent any effect this parameter may have produced in the model.

3. **APPROACH.** A Monte Carlo simulation model was created to assess the performance of the TIROS constellation. The groundrules and assumptions discussed above were coded into a computer model to govern system behavior throughout the simulation. The model then randomly creates hundreds of possible scenarios of what could happen given these behavioral constraints and input values. These scenarios are analyzed statistically to determine what is most likely to happen over the next several years. Some of the input values are then changed and the entire process performed again to assess the impact of each parameter on the overall system performance. The overall algorithm of the model is the following:

```
REPEAT FOR EACH OF 200 MISSIONS (11 YEARS)
        REPEAT FOR EACH MONTH
                1.      ATTEMPT ANY SCHEDULED LAUNCHES
                                (FAIL IF RANDOM # > LAUNCH Ps)
                2.      TEST ALL IN-ORBIT SATELLITES
                                (FAIL IF RANDOM # > CONDITIONAL Ps)
                3.      IF A SATELLITE FAILS, RE-ACTIVATE A BACK-UP AND
                        SCHEDULE A REPLACEMENT LAUNCH
                4.      IF A SATELLITE IS NEARING ITS DRIFT LIMIT,
                        SCHEDULE A REPLACEMENT LAUNCH
                                .
                                .
                N.      RECORD STATUS OF ALL SATELLITES FOR THAT MONTH
        UNTIL JULY 200.5
END
STATISTICALLY ANALYZE THE DATA FROM THESE 200 MISSIONS
```

Model outputs include a detailed log of events in each of the randomly generated scenarios. The model also outputs reliability curves, availability curves, mean values for each curve. and an expected launch schedule. Individual outputs are generated for both the AM and PM orbits. For each orbit, a complete set of outputs are provided for the requirement of one satellite in the orbit along with outputs for having [illegible] orbit.

Greater efficiency was possible since the model was created from other work performed recently by this office. The overall approach and most of the code was [illegible] validated. However, substantial modifications were required to accommodate the unique consuaints of the TIROS operations. Consequently. samples from the detailed log were manually checked to verify that the simulation was indeed following the desired behavioral constraints. Also, samples from each of type of output were manually checked against the detailed log to assure that the data reduction code was operating correctly.

4. RESULTS. The most basic output of the model is the hundreds of randomly generated possible scenarios of what could happen over the next several years. One such is scenario is show-n in Table 2.

TABLE 2
TYPICAL **TIROS** SCENARIO

Month	Satellite	Orbit	Event
0	NOAA-9	PM	operational as a backup
0	NOAA-10	AM	operational as a backup
0	NOAA-11	PM	operational
0	NOAA-12	AM	operational
3	NOAA-11	PM	FAILED • '** ACTIVE S/C *****
3	NOAA-9	PM	RE-ACTIVATED to primary status
6	NOAAJ	PM	LAUNCHED
a	NOAA-J	PM	NOW FULLY OPERATIONAL
a	NOAA-9	PM	now a back-up s/c
25	NOAA-9	PM	Failed while a backup satellite
29	NOAA-10	AM	Failed while a backup satellite
48	NOAA-K	PM	launch scheduled
52	NOAA-K	PM	LAUNCH FAILED
52	NOAA-L	PM	launch scheduled
56	NOAA-L	PM	LAUNCHED
58	NOAA-L	PM	NOW FULLY OPERATIONAL
58	NOAA-J	PM	now a back-up s/c
98	NOAA-M	PM	launch scheduled
98	NOAA-J	PM	Failed while a backup satellite
102	NOAA-M	PM	LAUNCHED
104	NOAA-M	PM	NOW FULLY OPERATIONAL
104	NOAA-L	PM	now a back-up s/c

All other outputs from the model result from statistical analysis of hundreds of these possible scenarios. The simplest statistics, shown in Table 3, are the average times that the TIROS constellation could be expected to perform at various levels.

The graphical outputs from the model include reliability curves and availability curves. Reliability curves show the probability of maintaining continuous coverage from the beginning of the simulation through some date along the x-axis. These curves represent service without interruption. They are always a decreasing function of time since it becomes less likely that one would experience absolutely no interruptions as the time period increases. The availability curves, on the other hand, show the probability of having service on any date along the x-axis. These curves usually decrease as satellites age and then rebound somewhat as new satellites are manufactured. The magnitude of the rebound is most dependent on launch vehicle reliability.

TABLE 3
TIROS SIMULATION RESULTS

PERFORMANCE MEASURE	MEAN
Continuous coverage by ONE or more AM satellites	79 months
Continuous coverage by TWO AM satellites	26 months
Continuous coverage by ONE or more PM satellites	106 months
Continuous coverage by TWO PM satellites	36 months
Average time with NO AM satellite	8.4 montbs
Average time with ONE AM satellite	82 months
Average time with TWO AM satellites	41 months
Average time with NO PM satellite	4.4 months
Average time with ONE PM satellite	50 months
Average time with TWO PM satellites	78 months
Average number of AM outages	1.2
Average duration of an AM outage	6.8 months
Average number of PM outages	0.56
Average duration of a PM outage	7.9 months

Some other interesting observations from the baseline case scenarios include the fact that, during the 1 l-year study, NOAA-N is only launched in about 80% of the scenarios and that NOAA-N' is only launched in 70% of the scenarios. While NOAA-J always launches into the PM orbit, the model determines where the other satellites launch based on the need at the time of launch. The orbits assigned to each satellite breaks out roughly as shown in Table 4.

TABLE 4
ORBIT ASSIGNMENTS

SATELLITE	PM	AM	NOT LAUNCHED
NOAA-J	100%	0%	0 %
NOAA-K	70%	30%	0%
NOAA-L	60%	40%	0%
NOM-M	50%	50%	0%
NOAA-N	50%	30%	20%
NOAA-N'	60%	1 0%	30%

Also of interest is the most probable launch dates for each satellite. In short most of the launches occur at random tunes throughout the 11 years; however, some dates stand out as particularly likely. These most likely dates often coincide with the production delivery dates for new satellites. In that case, the high need for a launch on that date results from the fact that the new satellite was really needed earlier but was not yet available for launch The most likely launch dates are summarized in Table 5.

TABLE 5
MOST LIKELY LAUNCH DATES

DATE	NEED	SATELLITE
DEC 94	100%	NOAA-J
JAN 96	33%	NOAA-K
DEC 96	26%	NOM-L
AUG 97	20%	NOAA-M
OCT 98	65%	NOAA-K(30%)
		NOAA-L(26%)
		NOAA-M(10%)
APR 99	20%	NOAA-N
APR 00	20%	NOAA-N’
OCT 02	40%	NOAA-M

Figures 1 and 2 show the reliability and availability plots, respectively, for satisfying the PM orbit requirement with at least one satellite. Similarly, Figures 3 and 4 show the reliability and availability plots, respectively, for satisfying the AM orbit requirement with at least one satellite. The solid curve in each of these plots was generated by averaging the results from ten 200-scenario runs of the model. The thin vertical lines intersecting these curves represent the range, with 95% confidence, in which a curve from a single 200-pass run should fall. This range is important for interpreting the subsequent “what-if’ plots, since all of the “what-if’ curves were generated from single 200-pass runs. If a particular “what-if’ curve lies outside these ranges then one can 95% sure that the difference between the “what-if’ result and the baseline result is significant For comparison, these “what-if’ plots include both the baseline curve and the “what-if” curve.

The next set of plots, Figures 5 and 6, show the availability of two-satellite service in the PM and AM orbits. respectively. These plots are included to illustrate the degree of on-orbit redundancy which may exist at various times over the next 11 years. It is important to note that the second satellite, or back-up, is usually not fully capable due to either failure of some non-critical component, orbital drift_ or the fact that it has not completed its initial on-orbit check-out and calibration. Similarly, the “at least one satellite” results shown throughout this report include some time, albeit small, in which that one satellite is a degraded back-up satellite. The curves represent the probability that the designated quantity of satellite(s), however degraded, will be available on-orbit They are not a measure of how degraded the satellite(s) may be.

The next plot. Figure 7, shows the availability for having both an AM and a PM satellite at any time over the next 11 years. This curve is the sum of the curves shown in Figures 2 and 4. The availability of service from either an AM or a PM satellite is not shown since it remains at 100% throughout the entire 11 years. Such a curve is the mathematical product of the curves shown in Figures 2 and 4.

FIGURE 1

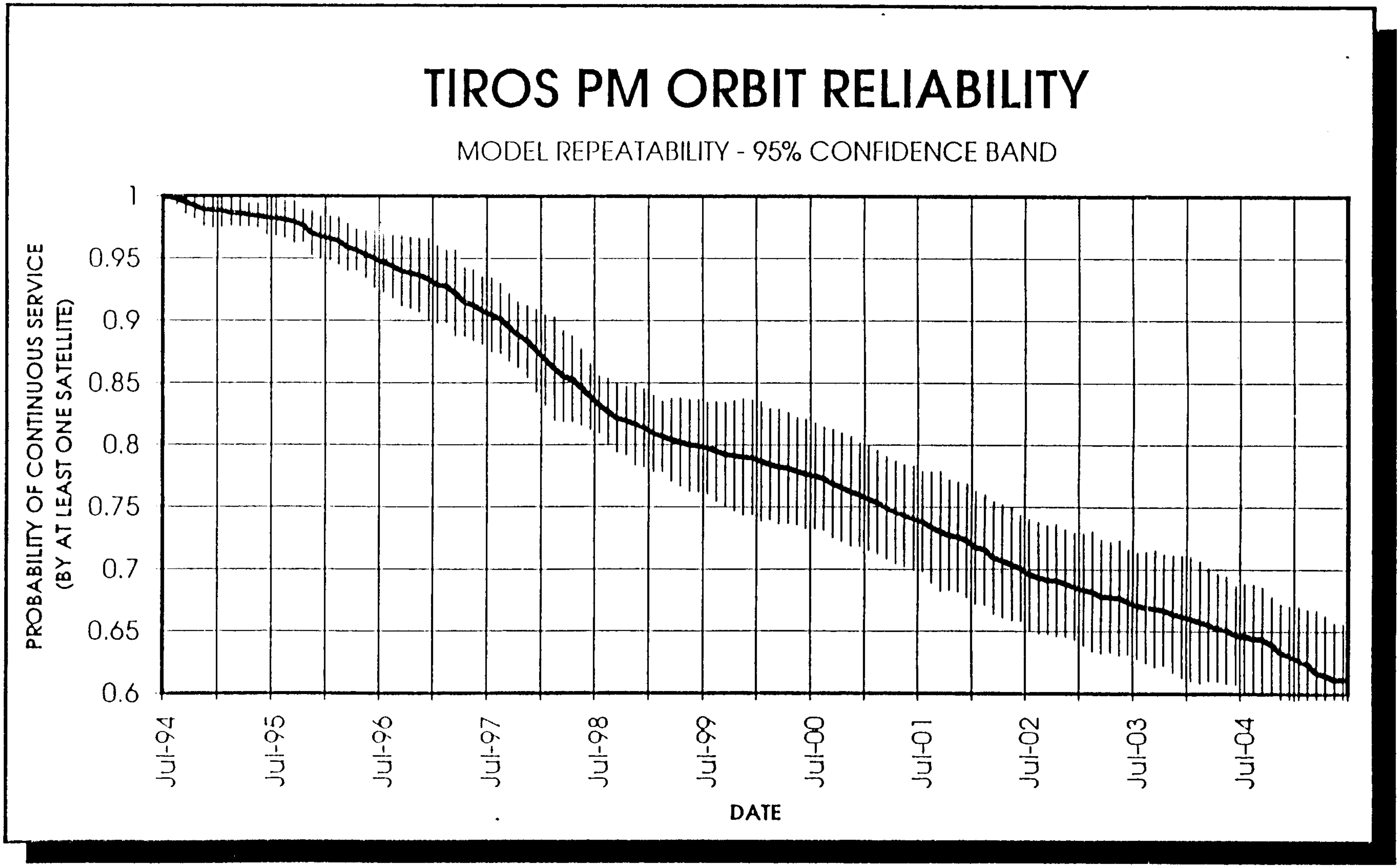

TIROS PM ORBIT RELIABILITY
MODEL REPEATABILITY - 95% CONFIDENCE BAND
PROBABILITY OF CONTINUOUS SERVICE
(BY AT LEAST ONE SATELLITE)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
Jul-94
Jul-95
Jul-96
Jul-97
Jul-98
Jul-99
Jul-00
Jul-01
Jul-02
Jul-03
Jul-04
DATE

FIGURE 2

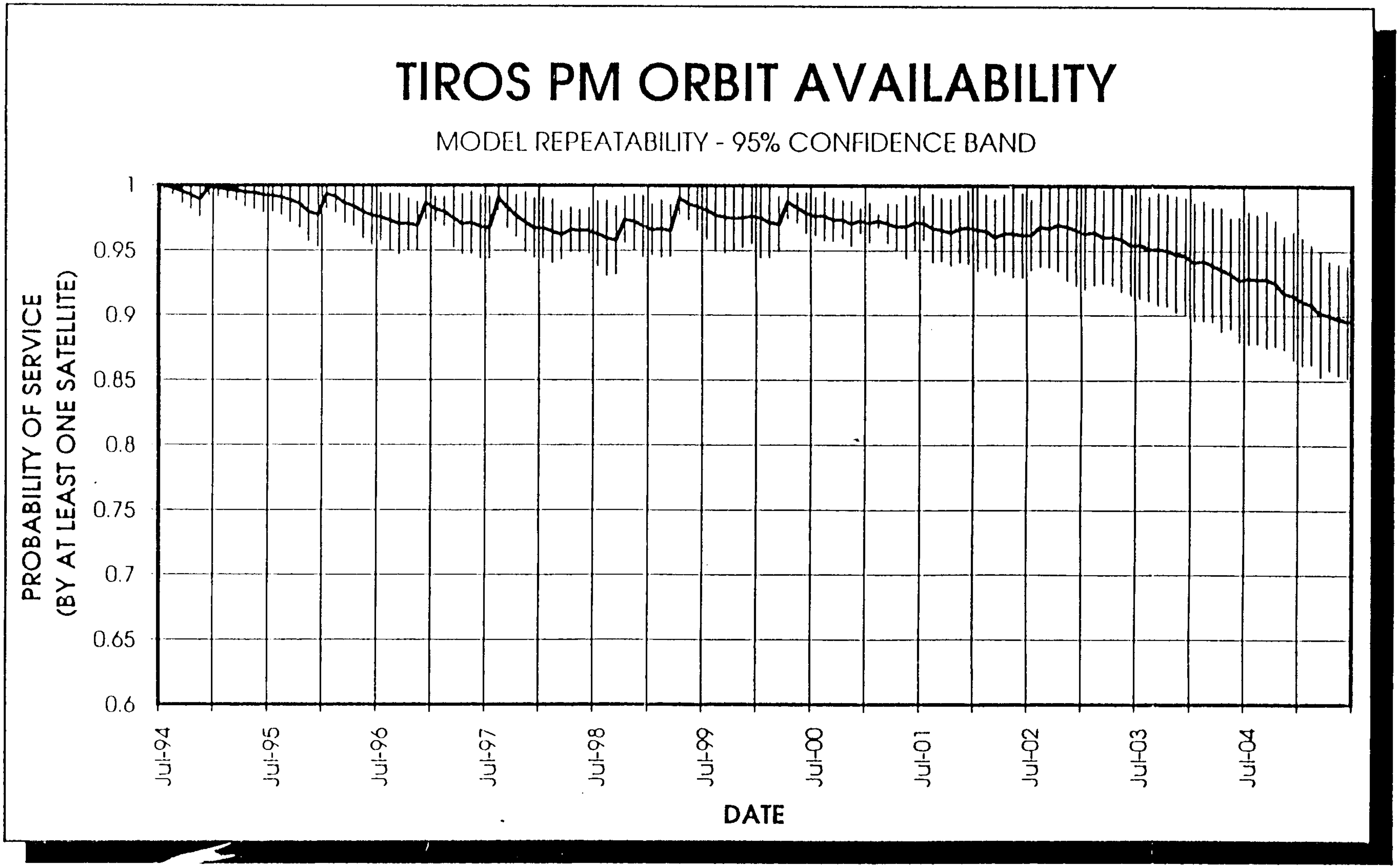

TIROS PM ORBIT AVAILABILITY
MODEL REPEATABILITY - 95% CONFIDENCE BAND
PROBABILITY OF SERVICE
(BY AT LEAST ONE SATELLITE)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
Jul-94
Jul-95
Jul-96
Jul-97
Jul-98
Jul-99
Jul-00
Jul-01
Jul-02
Jul-03
Jul-04
DATE

FIGURE 3

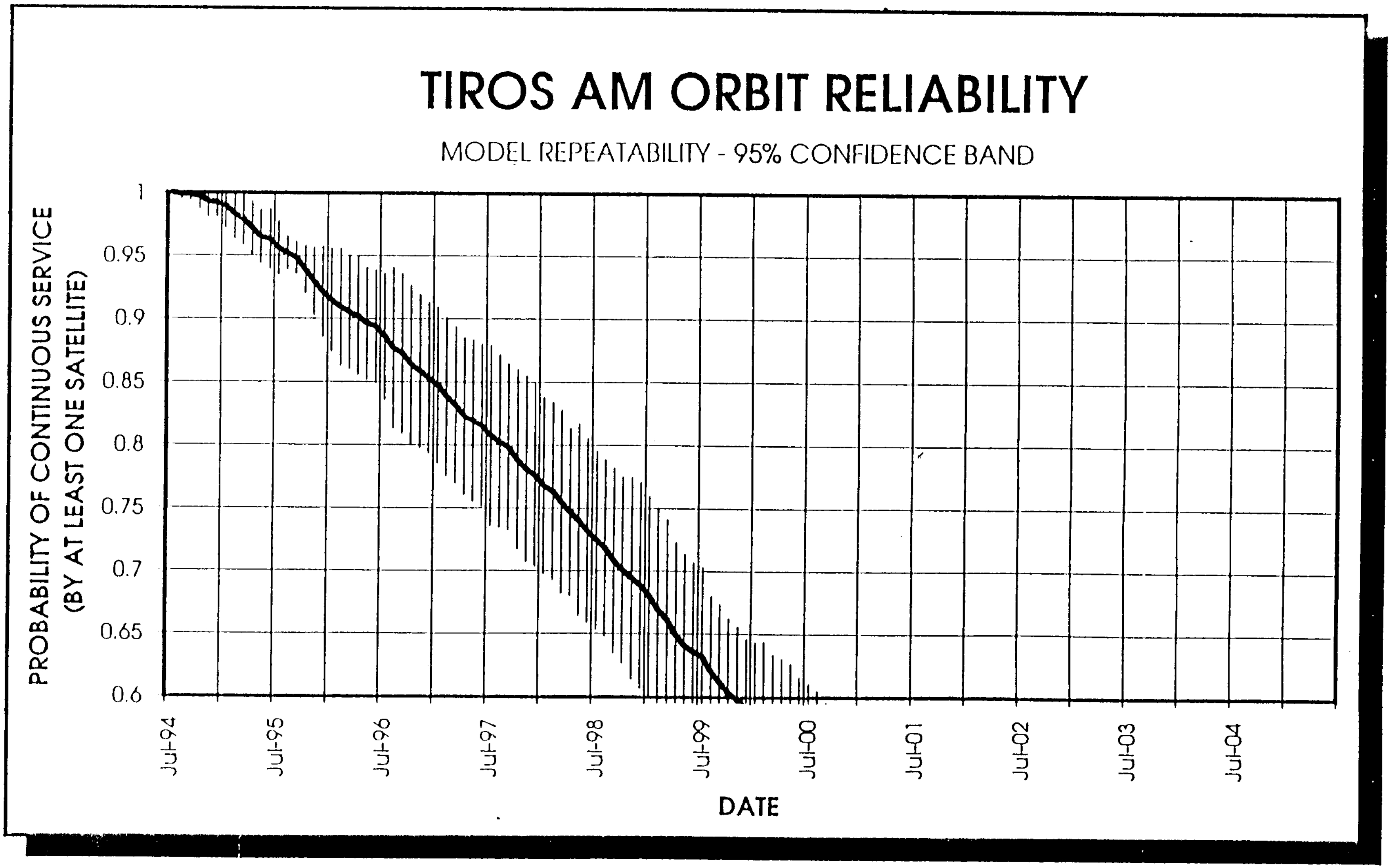

TIROS AM ORBIT RELIABILITY
MODEL REPEATABILITY - 95% CONFIDENCE BAND
PROBABILITY OF CONTINUOUS SERVICE
(BY AT LEAST ONE SATELLITE)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
Jul-94
Jul-95
Jul-96
Jul-97
Jul-98
Jul-99
Jul-00
Jul-01
Jul-02
Jul-03
Jul-04
DATE

FIGURE 4

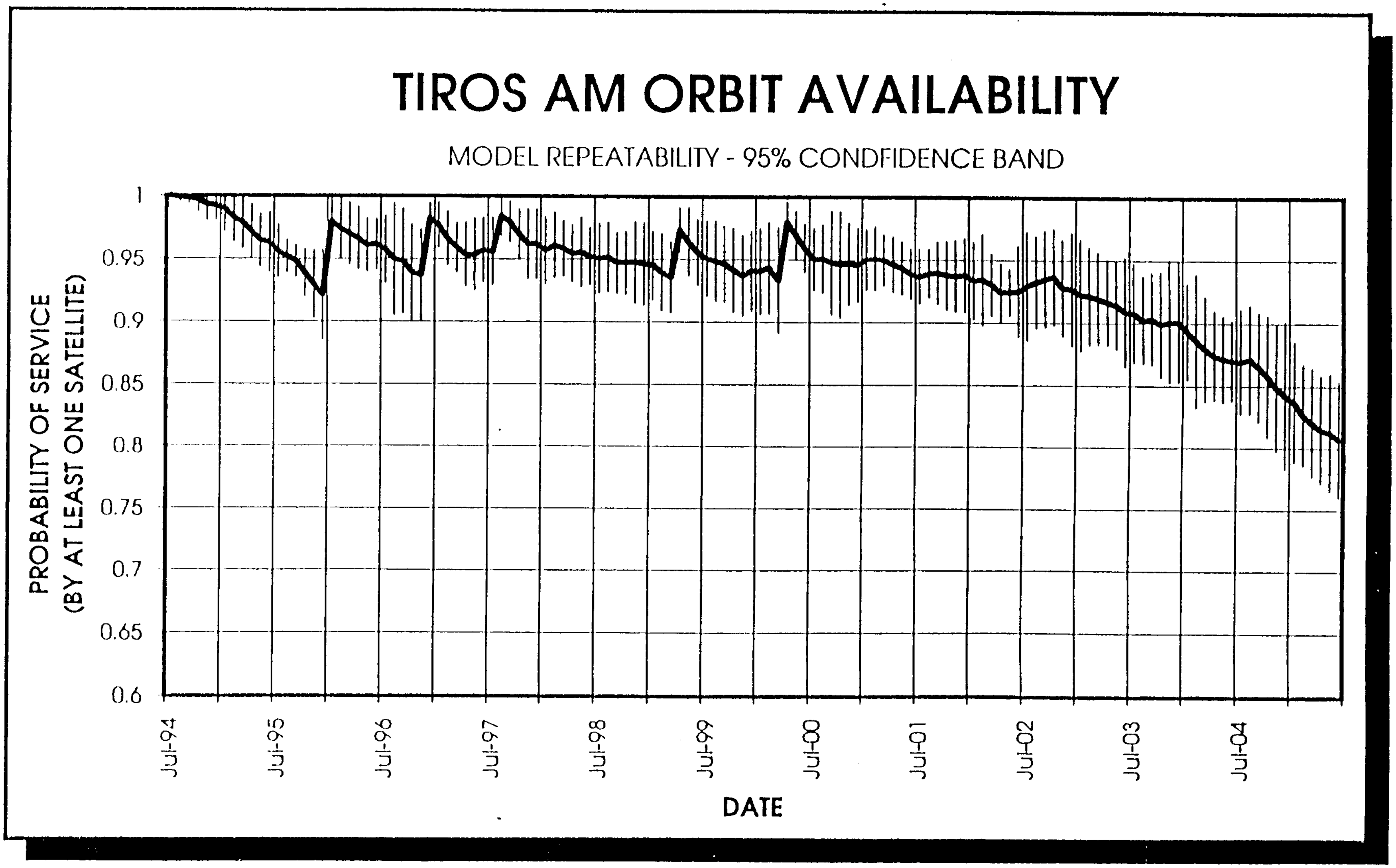

TIROS AM ORBIT AVAILABILITY
MODEL REPEATABILITY - 95% CONDFIDENCE BAND
PROBABILITY OF SERVICE
(BY AT LEAST ONE SATELLITE)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
Jul-94
Jul-95
Jul-96
Jul-97
Jul-98
Jul-99
Jul-00
Jul-01
Jul-02
Jul-03
Jul-04
DATE

FIGURE 5

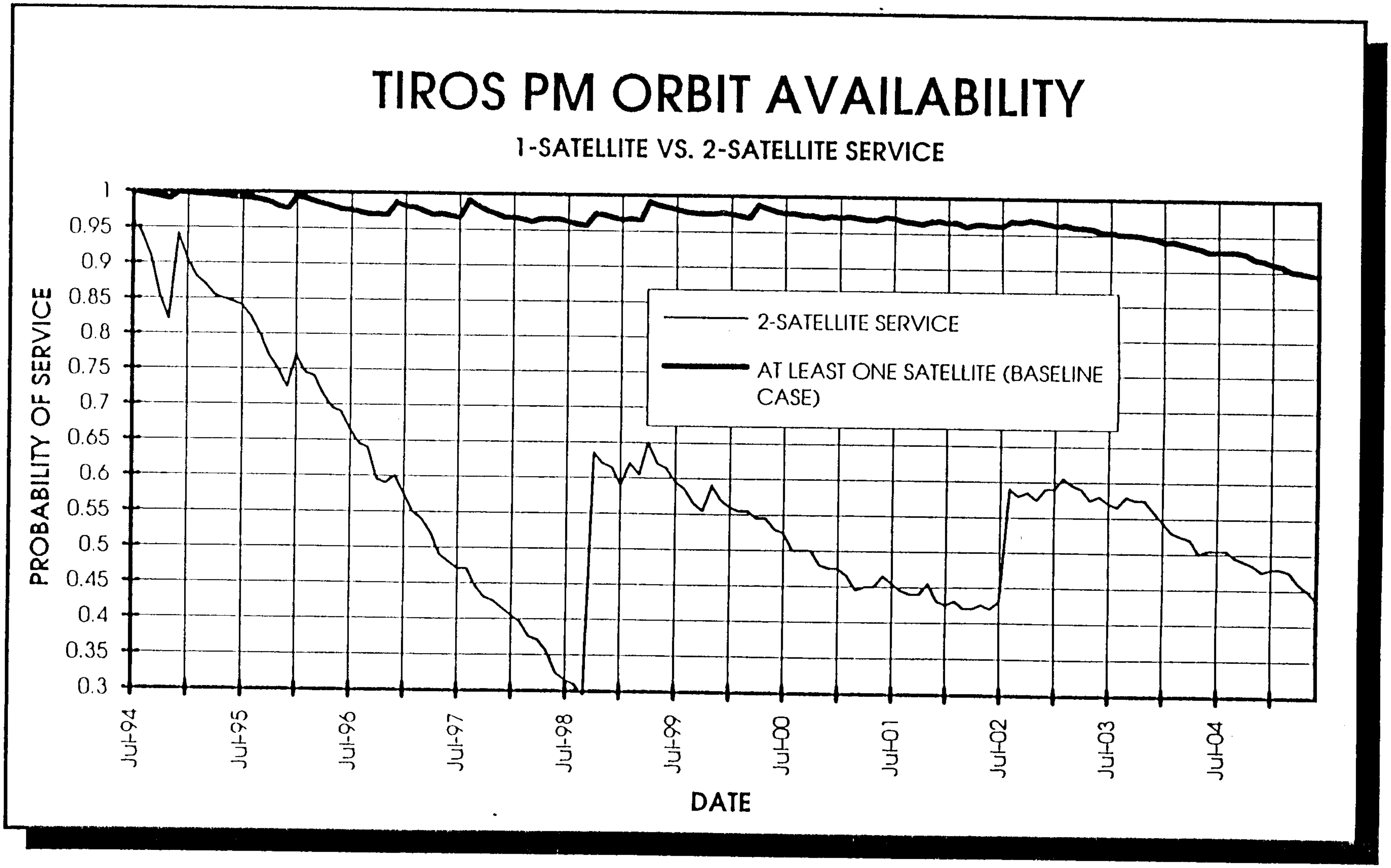

TIROS PM ORBIT AVAILABILITY
1-SATELLITE VS. 2-SATELLITE SERVICE
PROBABILITY OF SERVICE
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
2-SATELLITE SERVICE
AT LEAST ONE SATELLITE (BASELINE CASE)
Jul-94
Jul-95
Jul-96
Jul-97
Jul-98
Jul-99
Jul-00
Jul-01
Jul-02
Jul-03
Jul-04
DATE

FIGURE 6

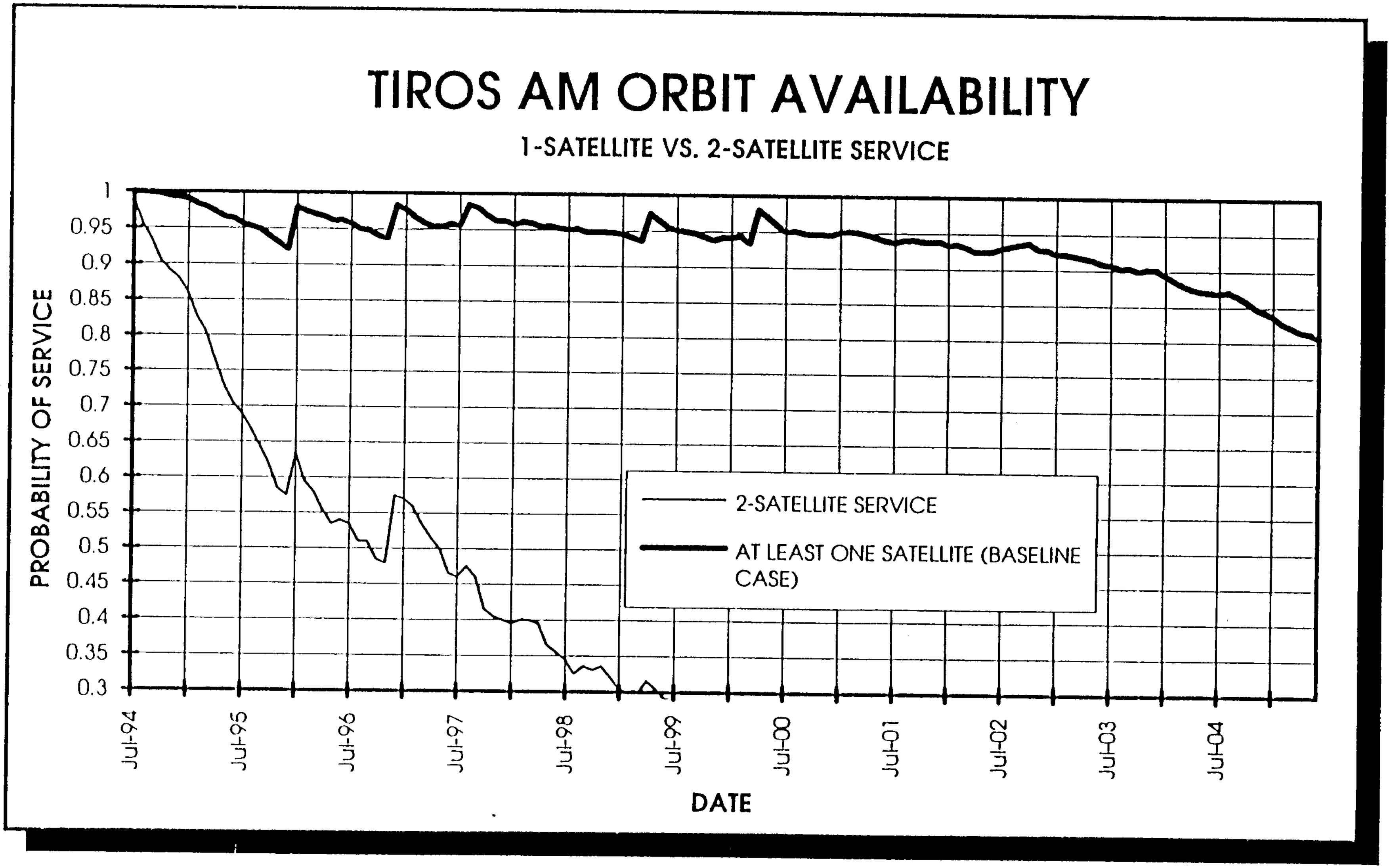

TIROS AM ORBIT AVAILABILITY
1-SATELLITE VS. 2-SATELLITE SERVICE
PROBABILITY OF SERVICE
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
Jul-94
Jul-95
Jul-96
Jul-97
Jul-98
Jul-99
Jul-00
Jul-01
Jul-02
Jul-03
Jul-04
DATE
2-SATELLITE SERVICE
AT LEAST ONE SATELLITE (BASELINE CASE)

FIGURE 7

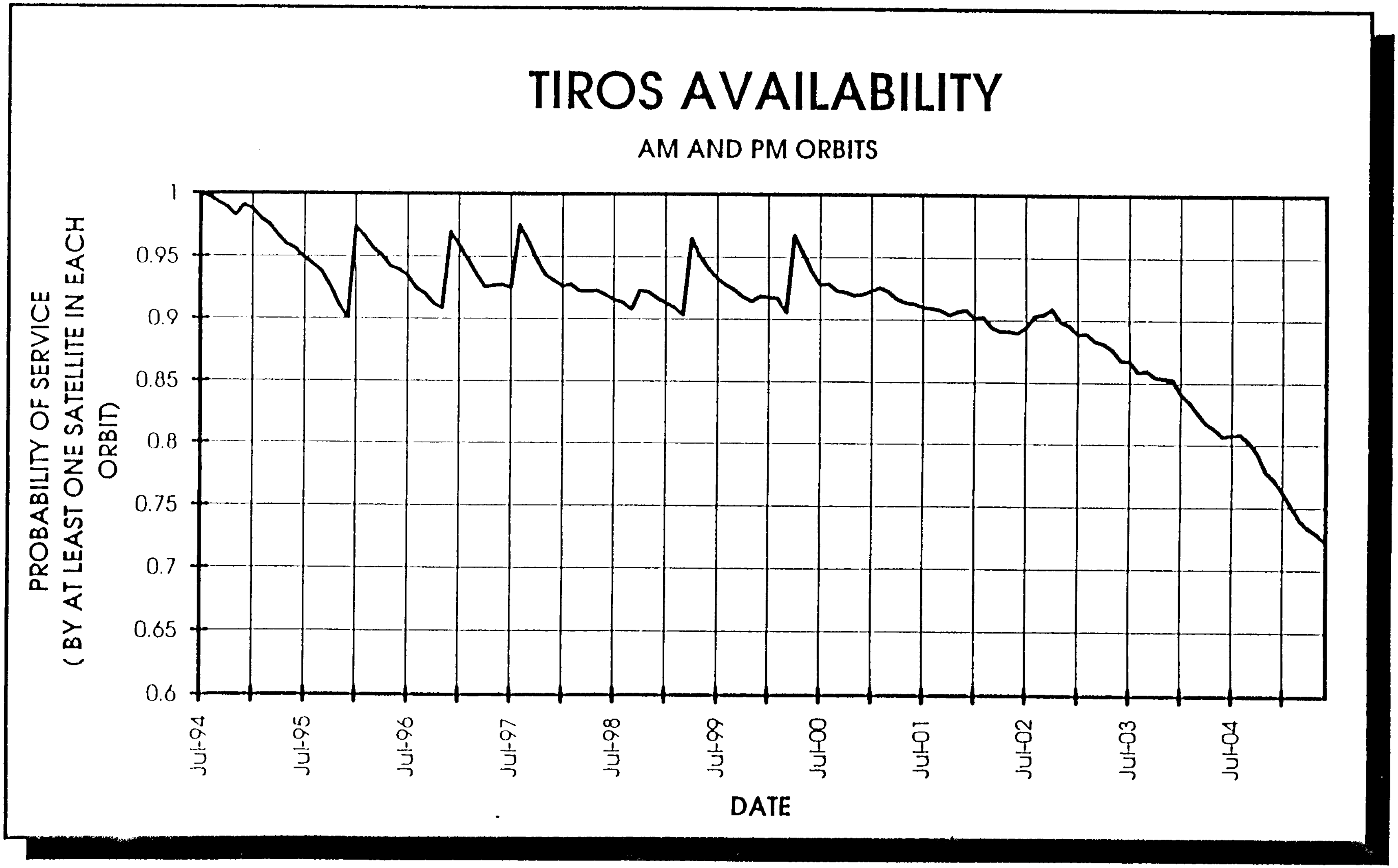

TIROS AVAILABILITY
AM AND PM ORBITS
PROBABILITY OF SERVICE
(BY AT LEAST ONE SATELLITE IN EACH ORBIT)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
Jul-94
Jul-95
Jul-96
Jul-97
Jul-98
Jul-99
Jul-00
Jul-01
Jul-02
Jul-03
Jul-04
DATE

Figure 8, on the other hand, answers the question, "What if the requirement were strictly for continuous service rather than service most of the time?". The heavy curve illustrates continuous service from either an AM or PM satellite. This curve is the sum of the curves shown in Figures 1 and 3. The light curve shows the probability for continuous service from both an AM and a PM satellite. This curve is the mathematical product of the curves shown in Figures 1 and 3.

All of the subsequent plots were generated to assess the impact of the uncertainty associated with some of the input values. The first of these, Figures 9 and 10, answer the question, "What if the TIROS satellites really exhibit an exponential failure distribution rather than the observed Weibull distribution?" This could well be the case even though the curve fitting techniques show a much better fit to the Weibull with the limited amount of data available. Remember that the overall GSFC experience argues for the exponential distribution. Also, since satellites are comprised of many types of components each having its unique failure distribution and, no particularly dominate failure patterns were noted in the TIROS data, then one would expect satellite failures to occur at random intervals, hence an exponential distribution. Figures 9 and 10, for the PM and AM orbits, respectively, show that when using the exponential distribution which best fits the available TIROS data, the overall system availability improved. At several points during the 11 years, this improvement exceeds the 95% confidence band on the baseline curves. This is especially the case for the AM orbit. Thus, this difference in failure distributions significantly impacts the results. The baseline case represents the more conservative estimate of system performance in this regard.

Figures 11 and 12, for the PM and AM orbits, respectively, answer the question, "What if our launch call-up response time is closer to 200 days rather than 120 days?" Regarding the PM orbit, the most significant impact is in 1998. There is really very little, if any, impact elsewhere during the 11 years. For the AM orbit, the impact starts during the latter half of 1998 and continues throughout the remaining time. In both cases. any significant impact is negative. In other words, the baseline case represents the more optimistic estimate of system performance in this regard.

Figures 13 and 14, for the PM and AM orbits, respectively, answer the question, "What if it takes the PM satellites 5 years to drift out of the specified orbit rather than 4 years?" This change appears to have very little, if any, impact since the resulting availability curves lie within the 95% confidence band of the baseline curves. One might reasonably expect that the 5-year drift life would delay when a new satellite, e.g., NOAA-O, would be needed. However. these curves appear to track the baseline curves all the way out through 2005. This suggests that satellite failure, rather than orbital drift., is the dominate reason for launching replacement satellites. The model is insensitive to the drift life in the range of 4-5 years. Further experimentation would be required to identify the minimum drift life below which the results would differ significantly from the baseline case.

Figures 15 and 16, for the PM and AM orbits, respectively, answer the question, "What if NOAA-11 had already failed prior to the start of the simulation?" The PM orbit initially shows degraded availability but fully recovers by 1997, if not sooner. Both orbits appear

FIGURE 8

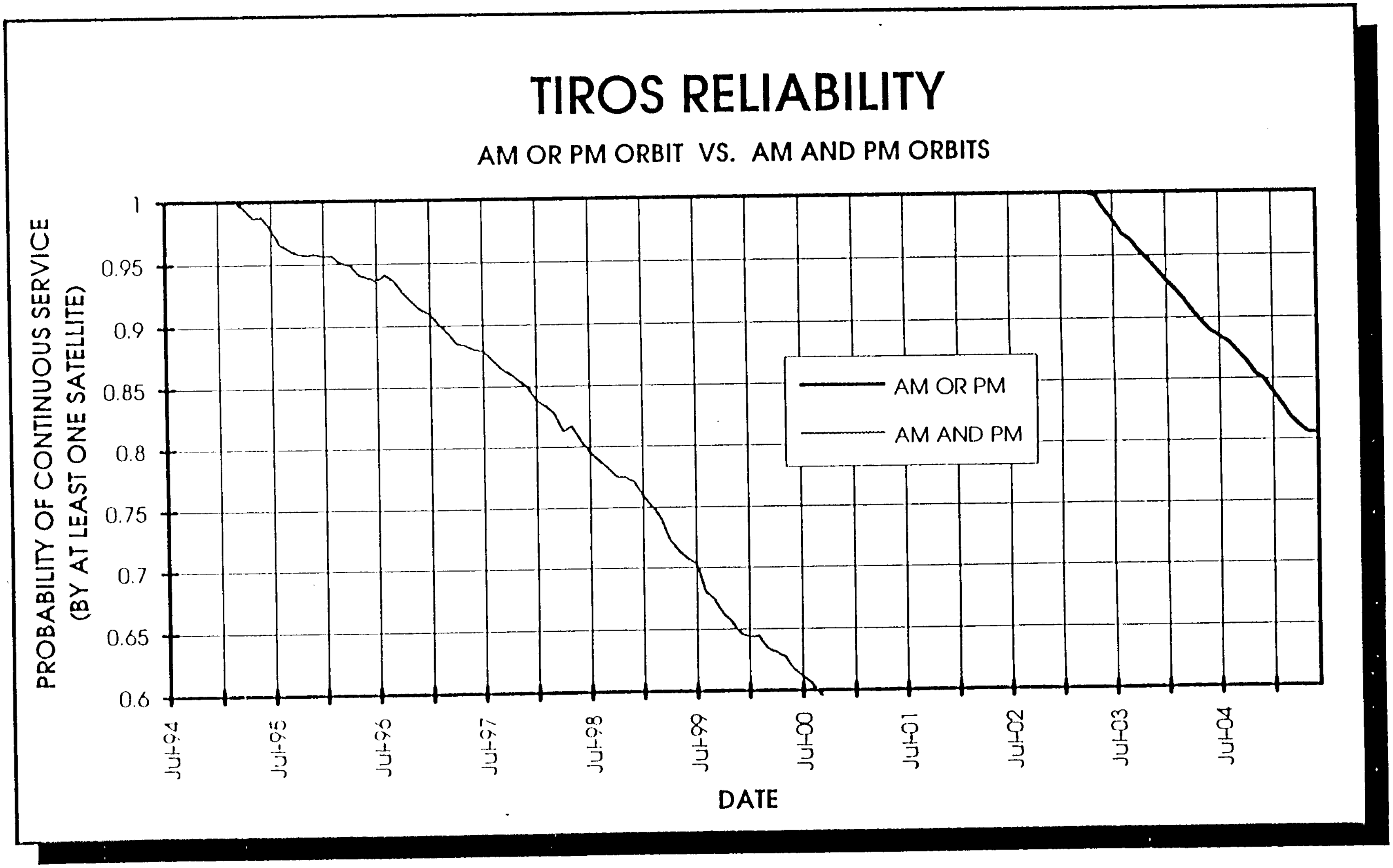

TIROS RELIABILITY
AM OR PM ORBIT VS. AM AND PM ORBITS
PROBABILITY OF CONTINUOUS SERVICE
(BY AT LEAST ONE SATELLITE)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
AM OR PM
AM AND PM
Jul-94
Jul-95
Jul-96
Jul-97
Jul-98
Jul-99
Jul-00
Jul-01
Jul-02
Jul-03
Jul-04
DATE

FIGURE 9

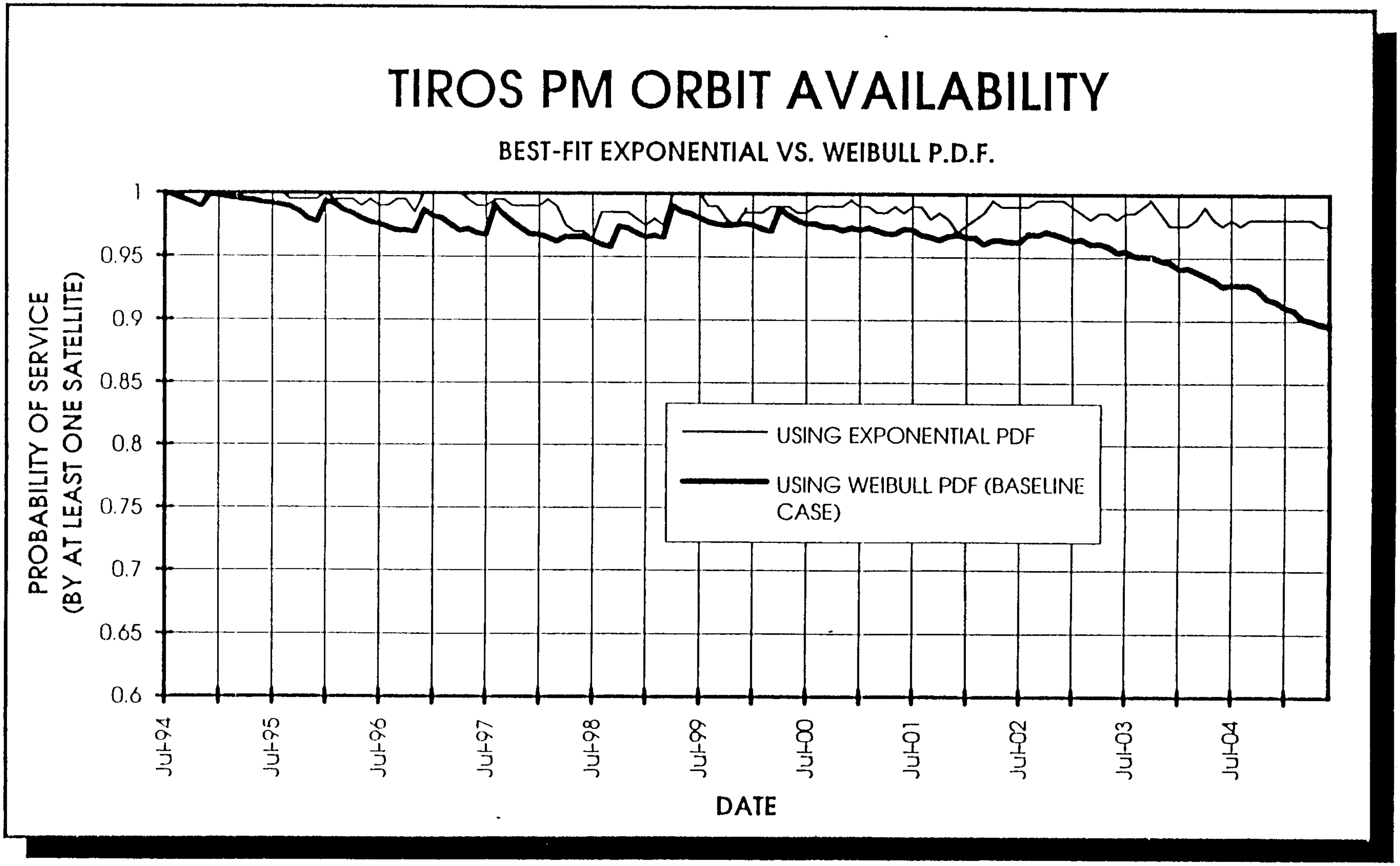
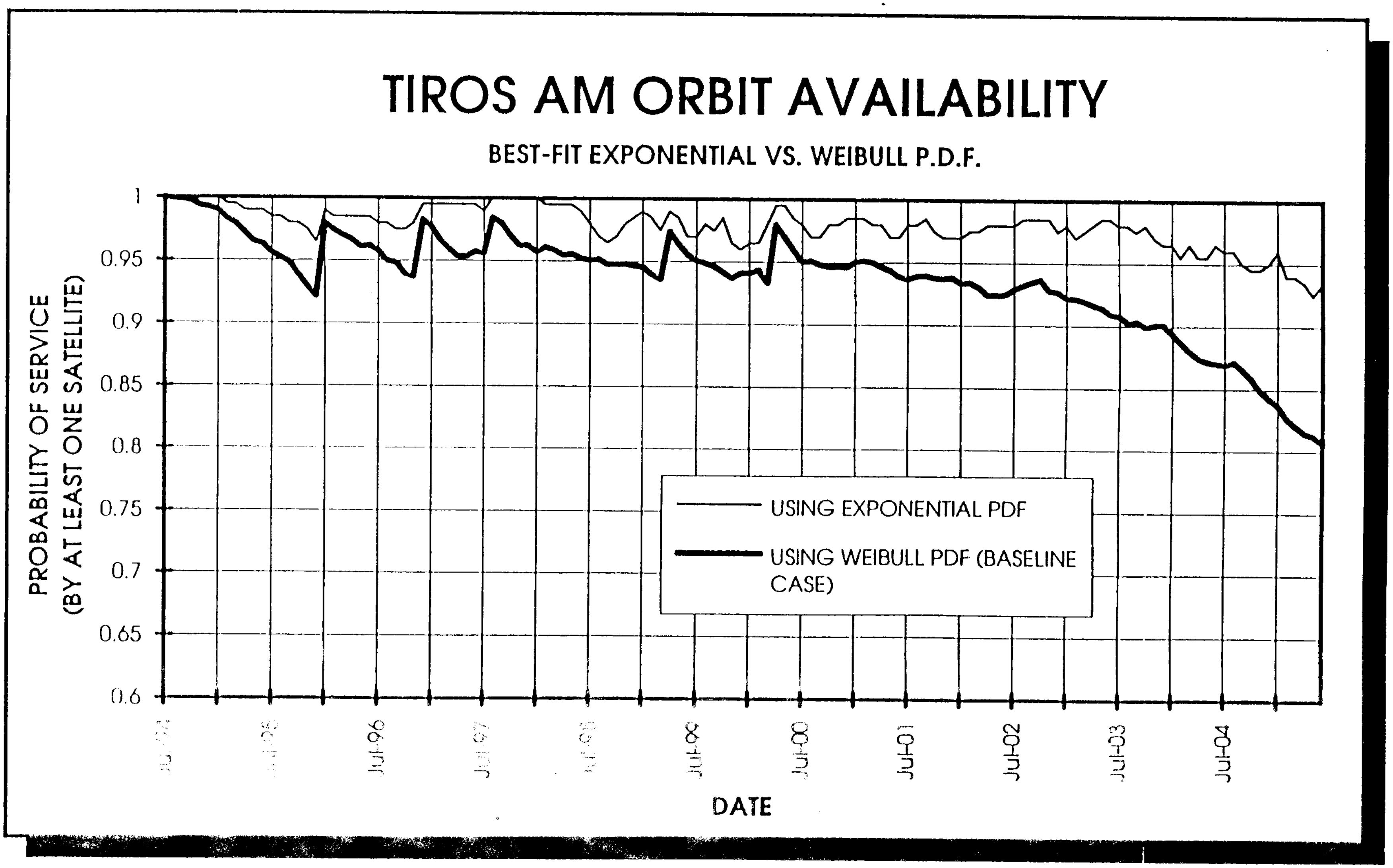

TIROS PM ORBIT AVAILABILITY
BEST-FIT EXPONENTIAL VS. WEIBULL P.D.F.
PROBABILITY OF SERVICE
(BY AT LEAST ONE SATELLITE)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
USING EXPONENTIAL PDF
USING WEIBULL PDF (BASELINE CASE)
Jul-94
Jul-95
Jul-96
Jul-97
Jul-98
Jul-99
Jul-00
Jul-01
Jul-02
Jul-03
Jul-04
DATE

FIGURE 10



TIROS AM ORBIT AVAILABILITY
BEST-FIT EXPONENTIAL VS. WEIBULL P.D.F.
PROBABILITY OF SERVICE (BY AT LEAST ONE SATELLITE)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
Jul-96
Jul-97
Jul-99
Jul-00
Jul-01
Jul-02
Jul-03
Jul-04
DATE
USING EXPONENTIAL PDF
USING WEIBULL PDF (BASELINE CASE)

FIGURE 11

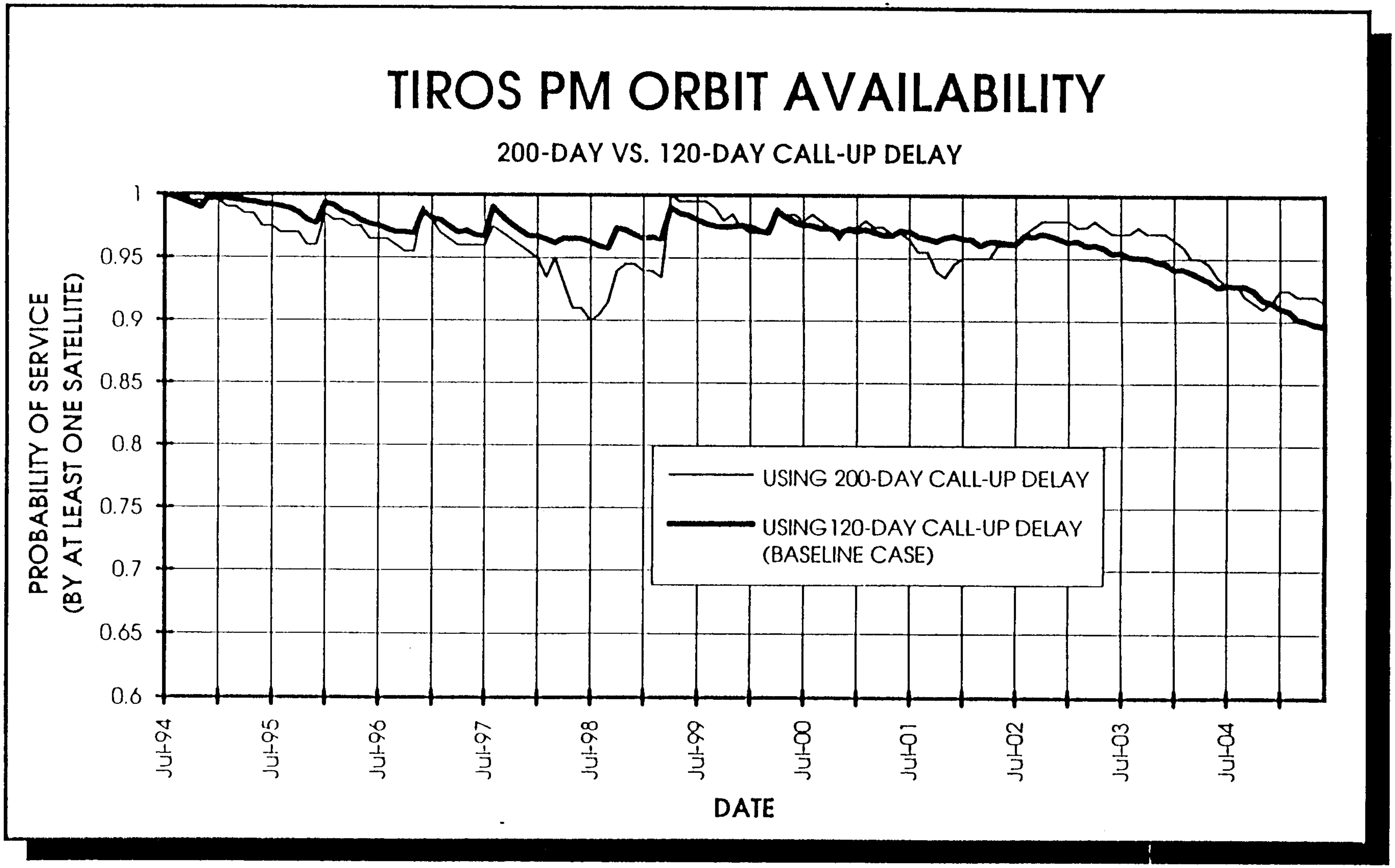

TIROS PM ORBIT AVAILABILITY
200-DAY VS. 120-DAY CALL-UP DELAY
PROBABILITY OF SERVICE (BY AT LEAST ONE SATELLITE)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
USING 200-DAY CALL-UP DELAY
USING 120-DAY CALL-UP DELAY (BASELINE CASE)
Jul-94
Jul-95
Jul-96
Jul-97
Jul-98
Jul-99
Jul-00
Jul-01
Jul-02
Jul-03
Jul-04
DATE

FIGURE 12

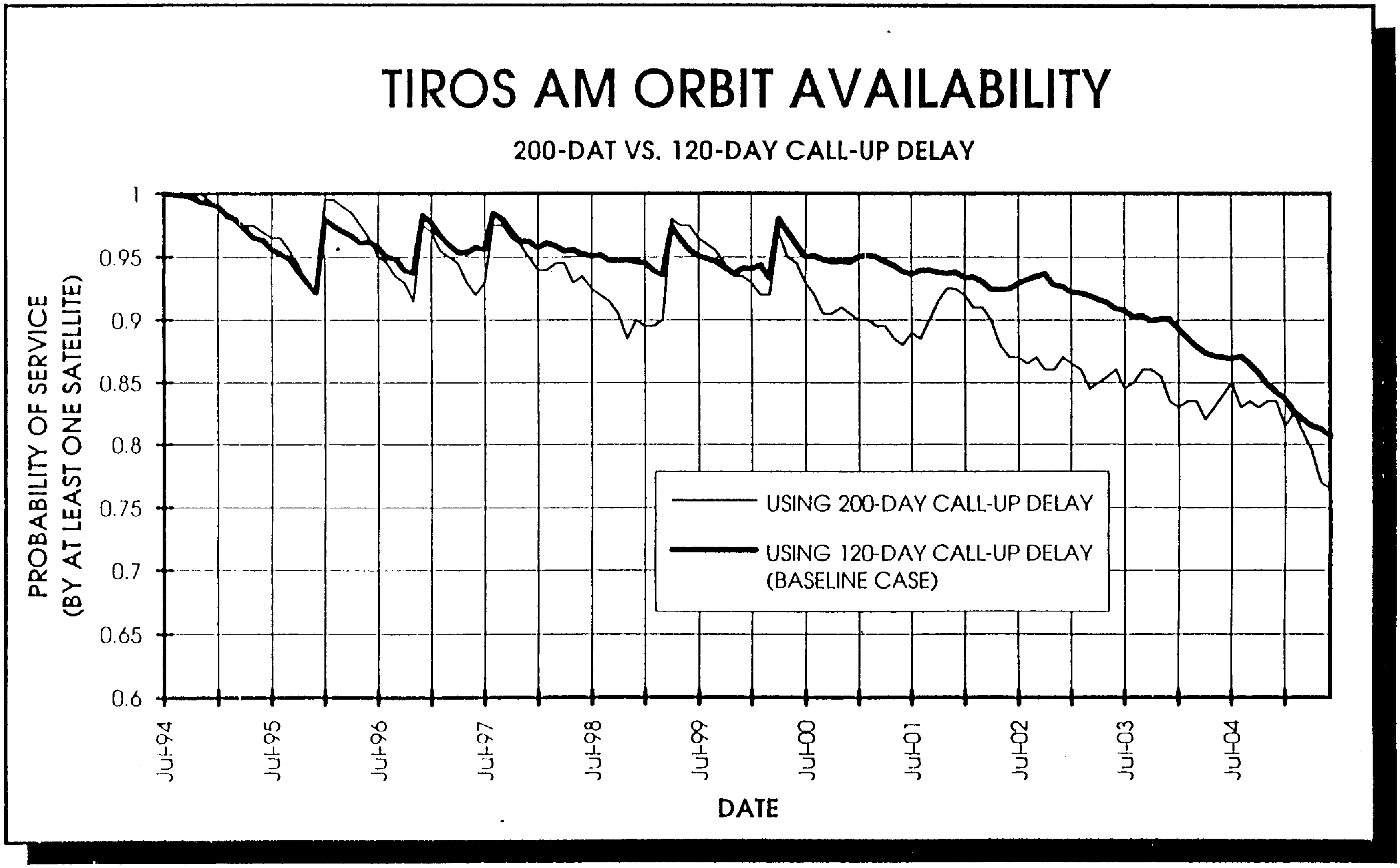

TIROS AM ORBIT AVAILABILITY
200-DAT VS. 120-DAY CALL-UP DELAY
PROBABILITY OF SERVICE
(BY AT LEAST ONE SATELLITE)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
Jul-94
Jul-95
Jul-96
Jul-97
Jul-98
Jul-99
Jul-00
Jul-01
Jul-02
Jul-03
Jul-04
DATE
USING 200-DAY CALL-UP DELAY
USING 120-DAY CALL-UP DELAY
(BASELINE CASE)

FIGURE 13

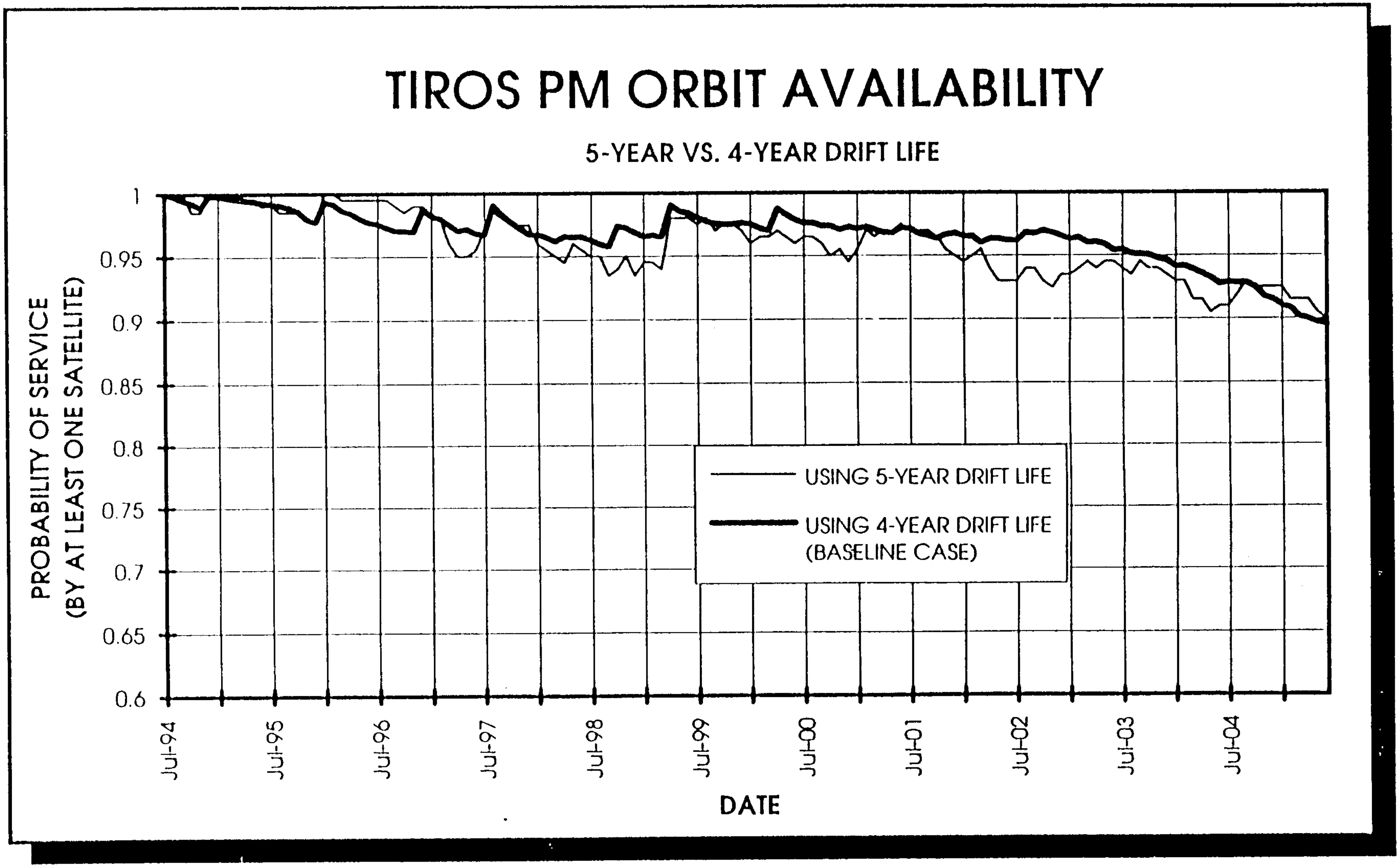

TIROS PM ORBIT AVAILABILITY
5-YEAR VS. 4-YEAR DRIFT LIFE
PROBABILITY OF SERVICE
(BY AT LEAST ONE SATELLITE)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
USING 5-YEAR DRIFT LIFE
USING 4-YEAR DRIFT LIFE
(BASELINE CASE)
Jul-94
Jul-95
Jul-96
Jul-97
Jul-98
Jul-99
Jul-00
Jul-01
Jul-02
Jul-03
Jul-04
DATE

FIGURE 14

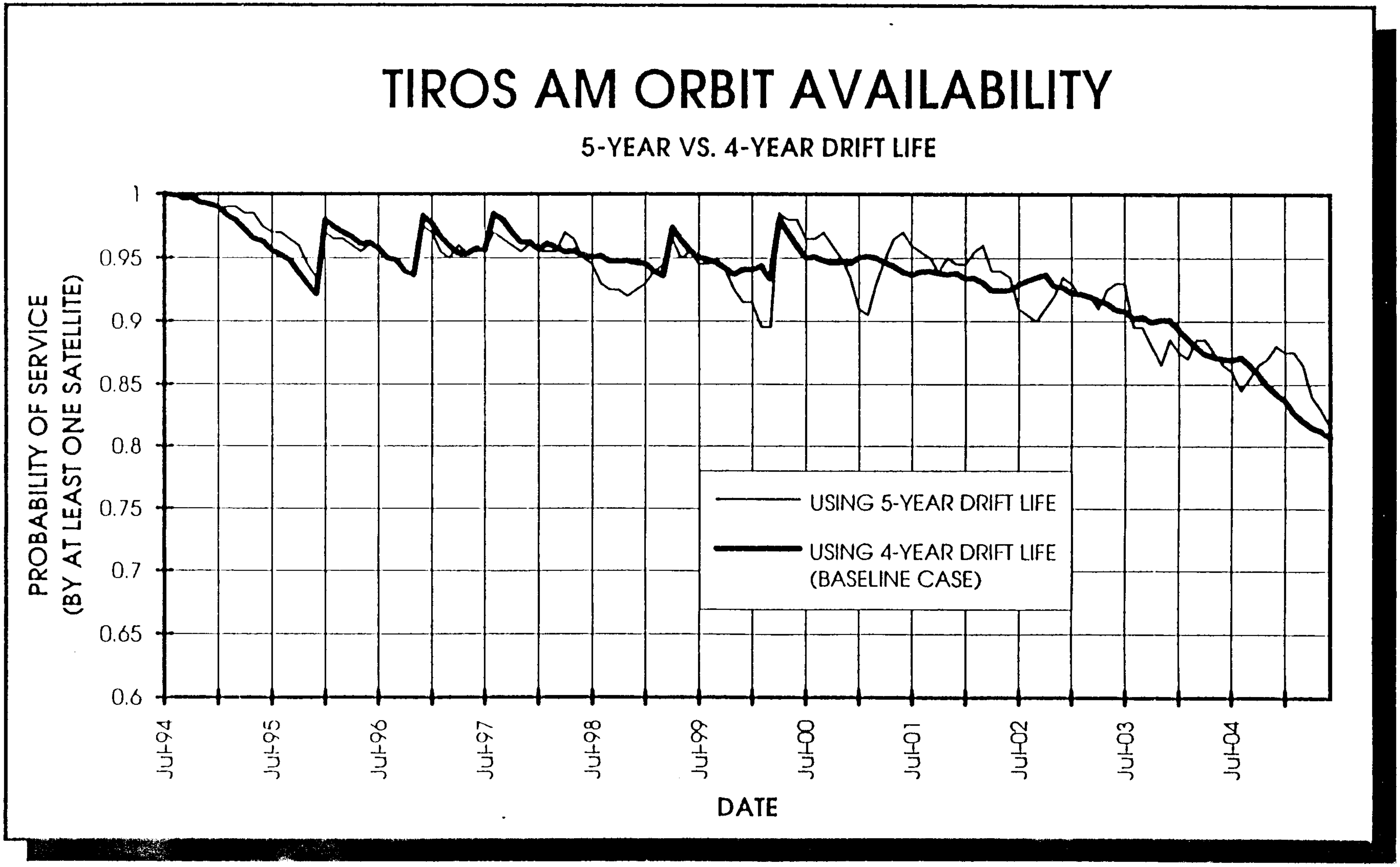

TIROS AM ORBIT AVAILABILITY
5-YEAR VS. 4-YEAR DRIFT LIFE
PROBABILITY OF SERVICE
(BY AT LEAST ONE SATELLITE)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
Jul-94
Jul-95
Jul-96
Jul-97
Jul-98
Jul-99
Jul-00
Jul-01
Jul-02
Jul-03
Jul-04
DATE
USING 5-YEAR DRIFT LIFE
USING 4-YEAR DRIFT LIFE
(BASELINE CASE)

FIGURE 15

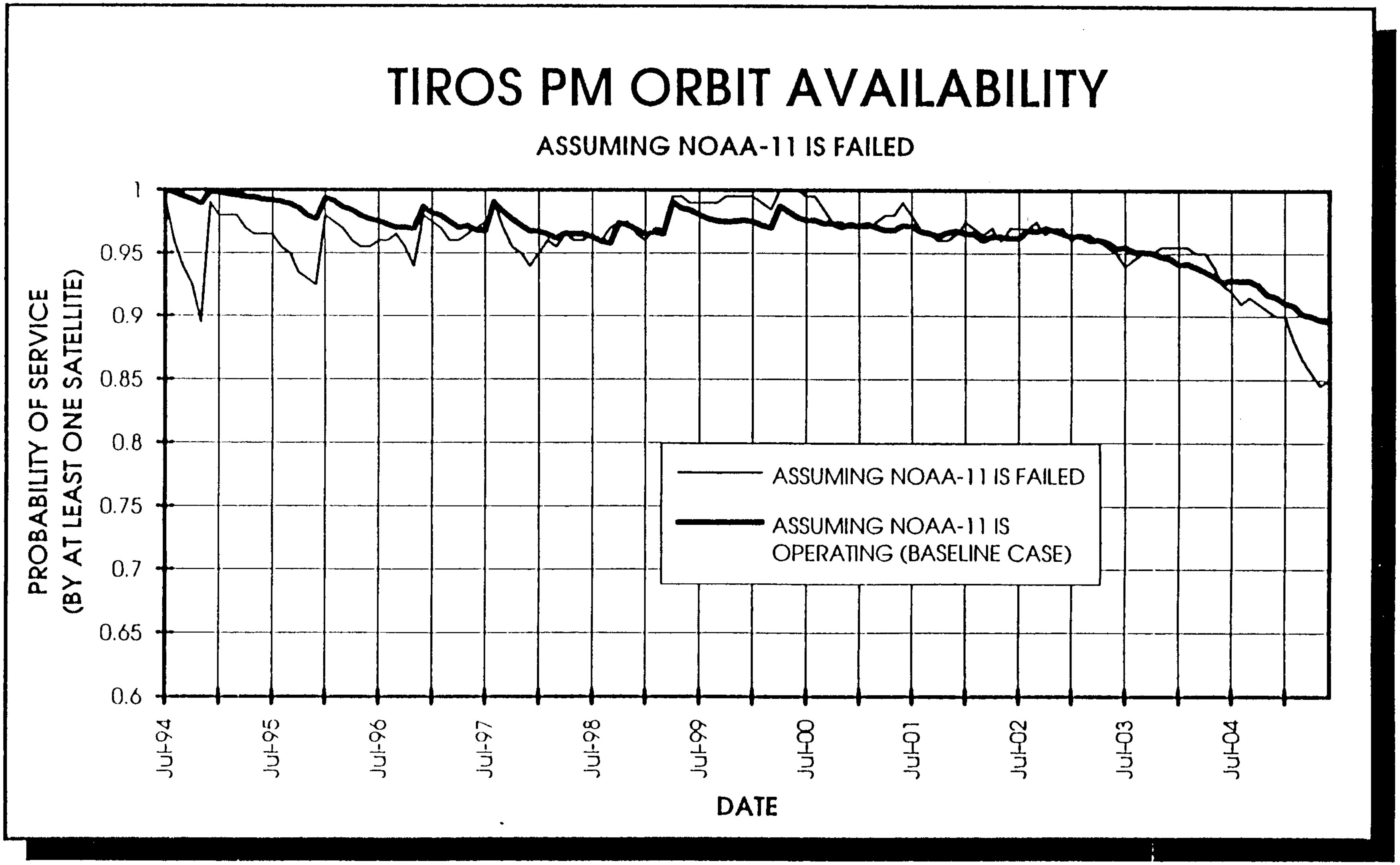
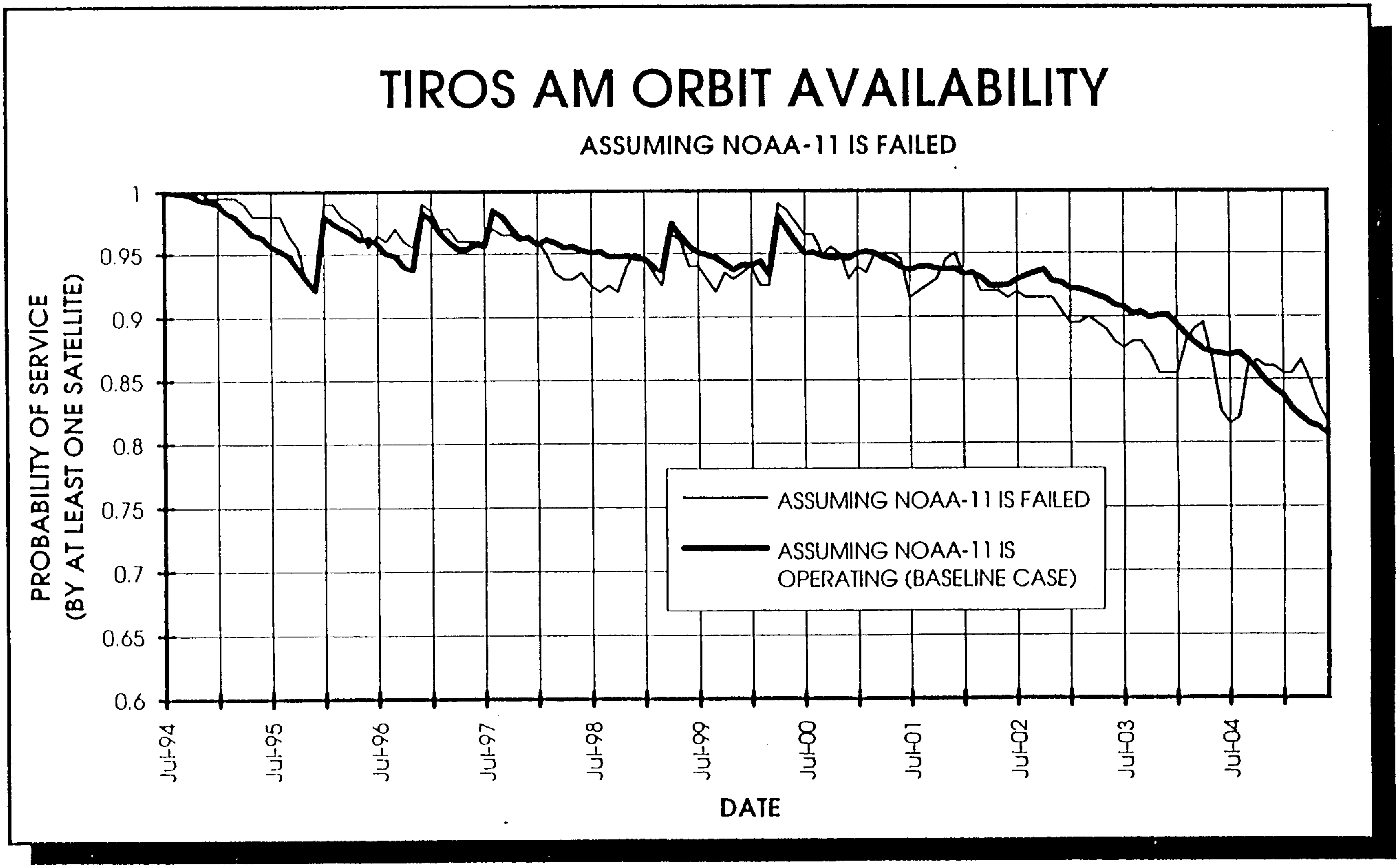

TIROS PM ORBIT AVAILABILITY
ASSUMING NOAA-11 IS FAILED
PROBABILITY OF SERVICE
(BY AT LEAST ONE SATELLITE)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
ASSUMING NOAA-11 IS FAILED
ASSUMING NOAA-11 IS OPERATING (BASELINE CASE)
Jul-94
Jul-95
Jul-96
Jul-97
Jul-98
Jul-99
Jul-00
Jul-01
Jul-02
Jul-03
Jul-04
DATE

FIGURE 16



TIROS AM ORBIT AVAILABILITY
ASSUMING NOAA-11 IS FAILED
PROBABILITY OF SERVICE (BY AT LEAST ONE SATELLITE)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
Jul-94
Jul-95
Jul-96
Jul-97
Jul-98
Jul-99
Jul-00
Jul-01
Jul-02
Jul-03
Jul-04
DATE
ASSUMING NOAA-11 IS FAILED
ASSUMING NOAA-11 IS OPERATING (BASELINE CASE)

to show more variability in the last year or two of the simulation; however, this variability is within the 95% confidence band on the baseline curves.

The final set of plots, Figures 17 and 18, for the PM and AM orbits, respectively, answer the question, "What if something caused us to slip the production schedule by one year beginning with NOAA-K?" The PM orbit is negatively impacted from mid-1996 through mid- 1997 since no replacement satellite is available for launch if needed. Otherwise, the PM orbit is unaffected by this slippage. The AM orbit similarly suffers beginning in mid-1996 but does not fully recover until 2000. This occurs most probably because the production schedule has not fully caught up with demand until 2000.

Table 6 compares some of the other results from each of the "what-if' exercises with the baseline case. The column labeled "Baseline Case (95%)" repeats the mean values which were shown in Table 3 and also the upper and lower limits which constitute a 95% confidence band. Shaded entries in the other columns indicate that the entry lies outside this 95% confidence band. Clearly, the exponential failure distribution differs significantly from the baseline case since every entry lies well outside of the 95% confidence band. The other columns only include a few entries outside of the 95% confidence band and, in many of these instances, the entry is only slightly outside.

TABLE 6
OTHER RESULTS COMPARISON

MEASURE	Baseline Case (95%)	Expon. PDF	200 Day Delay	5-Year Orbit Drift	NOAA-11 Failed	l-Year Sched. Slip	units
Continuous Service							
1+ AM	79±5	112	76	79	77	76	months
2 AM	26±3	55	24	26	25	25	months
1+ PM	106±3	119	100	102	92	103	months
2 PM	36±4	55	37	38	0	34	months
Avg. Time							
0 AM	8.4±1.7	2.8	12.0	8.5	8.9	11	months
1 AM	82±4	54	82	86	83	81	months
2 AM	41±4	75	38	37	40	40	months
0 PM	4.4f1.8	1.5	4.9	5.4	5.3	5.5	months
1 PM	50±4	30	50	54	61	52	months
2 PM	78±4	100	77	72	65	75	months
outages							
# of AM	1.2±0.1	0.5	1.3	1.3	1.3	1.2	
AM Length	6.8±1.2	5.3	9.0	6.8	7.0	9.1	months
# of PM	0.56±0.1	0.30	0.58	0.63	0.74	0.63	
PM Length	7.9±2.8	5.0	8.4	8.6	7.2	8.7	months

FIGURE 17

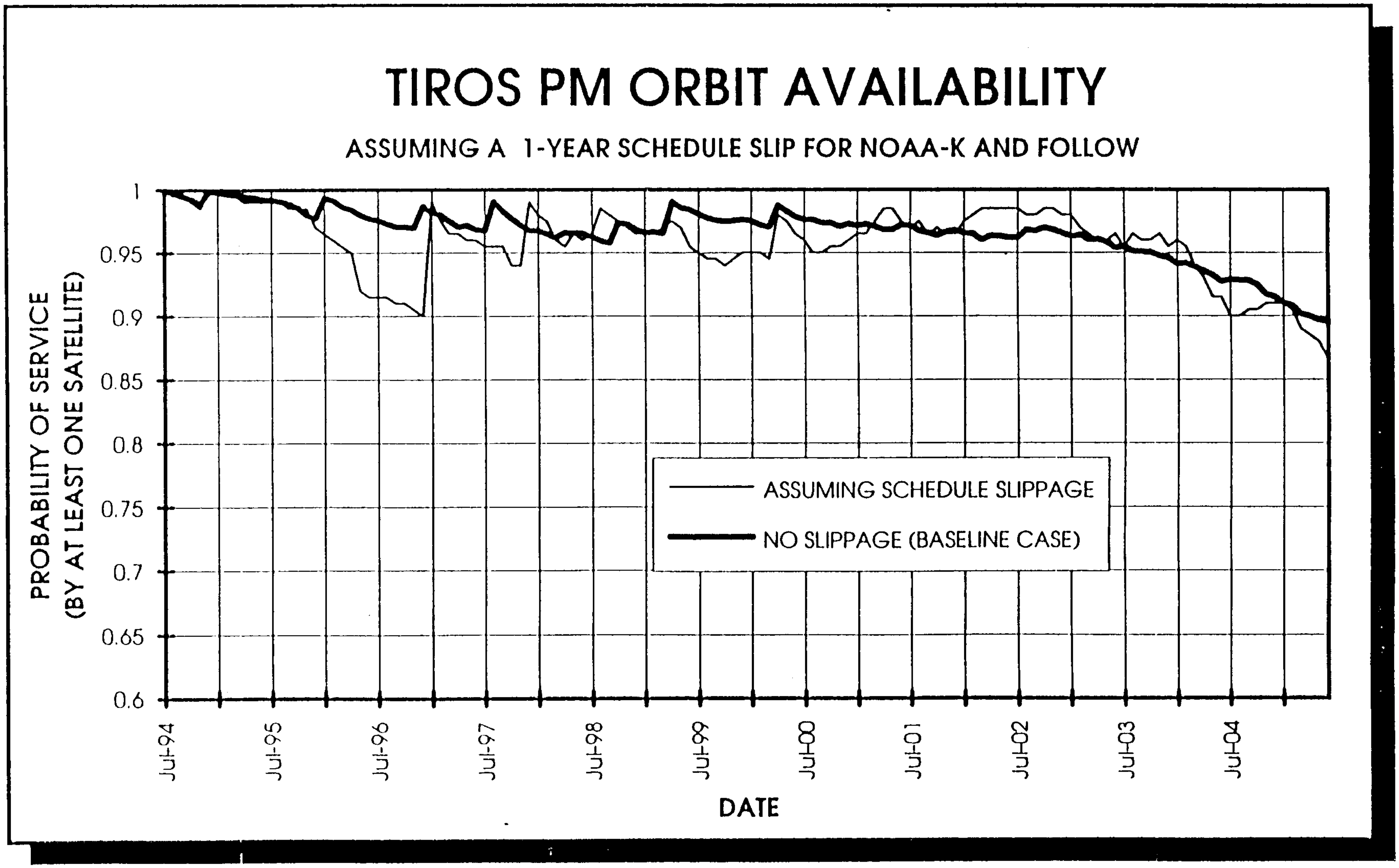
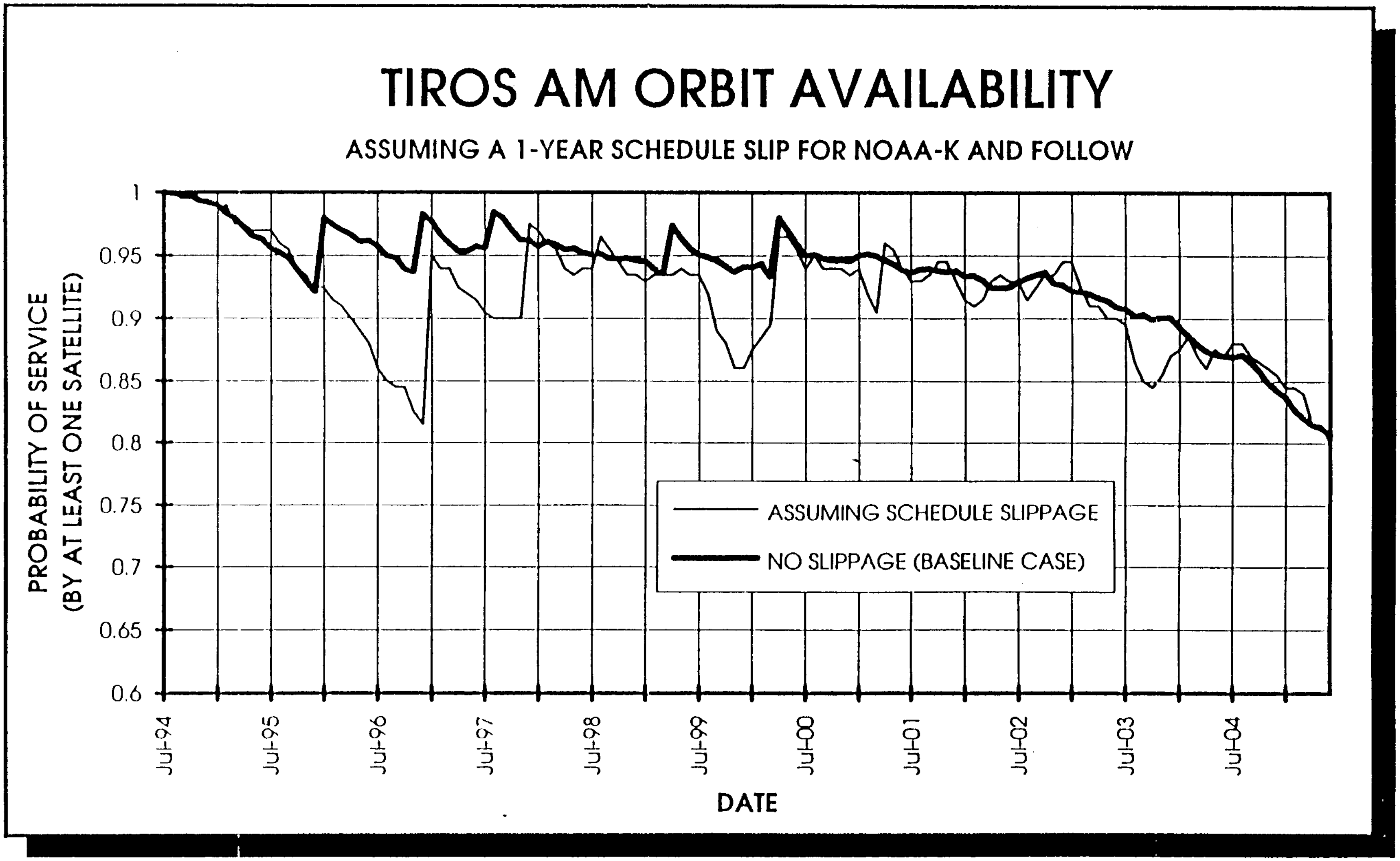

TIROS PM ORBIT AVAILABILITY
ASSUMING A 1-YEAR SCHEDULE SLIP FOR NOAA-K AND FOLLOW
PROBABILITY OF SERVICE
(BY AT LEAST ONE SATELLITE)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
ASSUMING SCHEDULE SLIPPAGE
NO SLIPPAGE (BASELINE CASE)
Jul-94
Jul-95
Jul-96
Jul-97
Jul-98
Jul-99
Jul-00
Jul-01
Jul-02
Jul-03
Jul-04
DATE

FIGURE 18


TIROS AM ORBIT AVAILABILITY
ASSUMING A 1-YEAR SCHEDULE SLIP FOR NOAA-K AND FOLLOW
PROBABILITY OF SERVICE
(BY AT LEAST ONE SATELLITE)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
Jul-94
Jul-95
Jul-96
Jul-97
Jul-98
Jul-99
Jul-00
Jul-01
Jul-02
Jul-03
Jul-04
DATE
ASSUMING SCHEDULE SLIPPAGE
NO SLIPPAGE (BASELINE CASE)

5. DISCUSSION. The constellation's performance is driven by the failure model for each satellite. The drift life of the PM orbit is generally not a factor in the steady-state performance of the constellation since the satellites have only a 50/50 chance of surviving 4.5 years after launch.

In general, the PM orbit performs better than the AM orbit. This is partially because the PM orbit (with its regular replacement intervals due to orbital drift) tends to have newer satellites than the AM orbit (with replacement only after failure). Also, the PM orbit is more likely to have a fully functioning on-orbit backup although it has probably drifted out of specification. These two facts produce a more shallow slope on the PM plots. The AM performance could be improved up to the level of PM performance by scheduling regular replacement intervals; however, the supply of replacement satellites would be consumed more rapidly.

Currently, the baseline data shows that an additional satellite (e.g., NOAA-O) is needed by the end of 2001 to maintain performance to the levels of the 1990's. This need date can be extended by about a year if PM orbit drift can be extended out to 5 years especially for the later launches. Such a situation may likely occur since NOAA-N and -N' are scheduled to launch on a new version of the Delta which is advertised to yield smaller insertion errors. Also, the need date for the next satellites can be extended if the mean lives of the TIROS satellites is actually better than the baseline data suggests. Again, this may well be the case since our experience with all GSFC satellites has shown that as the quantity of lifetime data increases then so do our mean life estimates.

6. **CONCLUSIONS AND RECOMMENDATIONS. The** expected availability of the TIROS constellation remains above 90%, for having both an AM and PM satellite, from now through 2001. An additional satellite will need to be ready for launch at that time in order to maintain the overall availability of the constellation. Several what-if exercises were studied to account for uncertainty in the input values used to arrive at these conclusions. In general, the conclusions did not change regardless of what reasonable input values were used. Also from these what-if exercises, it was determined that the baseline input values produced a conservative estimate of constellation performance. Of course, actual performance will not follow any of the plots generated in this study. In actuality, the satellites will either be available or not.

APPENDIX A
EXPENDABLE LAUNCH VEHICLE RELIABILITY

Bayesian Reliability Estimation for ELV's

Kevin Angelone

August 27, 1993

Bayesian Reliability Estimation for ELV's

Introduction

For analysis of ELV reliability two methods were considered. The first method examined was the method of moving averages. This is a very straightforward approach that predicts future reliability by calculating the number of successes divided by the number of launches over a certain range of previous launches (usually around 20). Another method considered was the Bayesian approach. The Bayesian approach held several advantages over the method of moving averages. One was the ability to deal with whole probability distributions instead of only one number. This advantage will allow the calculation of confidence limits to accompany the reliability figures. Anotheer advantage was in the application of the Bayesian method to new programs like Pegasus. With the method of moving averages it is hard to accurately predict future reliability based on only a few launches. Using a prior distribution in the Bayesian method allows calculation of future reliability with possibly better accuracy.

Bayesian Basics

The basic premise of the Bayesian approach is that future events (like future reliability) can be calculated by multiplying a prior knowledge of events by a selected sampling size. In this study, a prior reliability distribution was created for all launch vehicles. This was then multiplied by a sample of launches containing a consistent family of vehicles to produce a posterior distribution which showed future reliability.

The Beta Function

For the study of ELV's a Beta function u-as chosen as the prior distribution function. The B (x_0, n_0)

$$b_j := \frac{\Gamma(no)}{(\Gamma(xo)\cdot\Gamma(no - xo))} \cdot (p_j)^{(xo - 1)} \cdot (1 - p_j)^{(no - xo - 1)}$$

distribution can assume a variety of both symmetrical and asymmetrical shapes[1]. For 2 mean of 0.5, the general shapes range from bell-shaped to U-shaped.

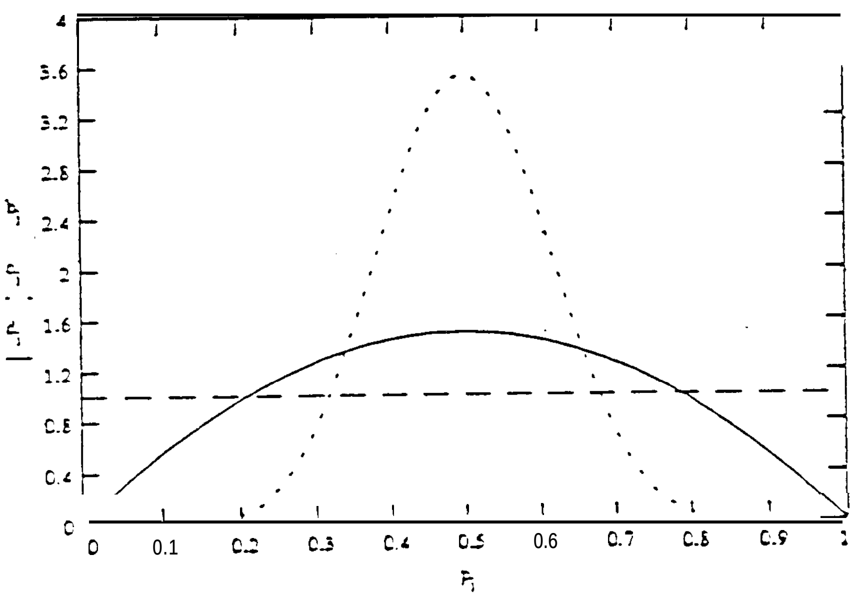


fig 1. Several Beta functions with mean 0.5

The Beta function was chosen because, unlike other functions like the exponential distribution, its probability density function (pdf) has two defined end points. Another advantage of the Beta function is that when it is multiplied by another Beta function, the result is another Beta function. This is very important to the study at hand because certain posterior distributions for current ELV's could eventually become prior distributions for future ELV's.

posterior distributions for current ELV's could eventually become prior distributions for future ELV's.

The Beta prior distribution for all calculations in this study was based on two assumptions concerning a genetic launch vehicle which generated constants used by the Beta function. The assumptions were:

1. Mean launch vehicle reliability of 85 %
2. 95 % confidence that launch vehicle reliability > 50%

This is a conservative estimate of prior launches due to the fact that no ELV has a success ratio anywhere near 50%. Using these two assumptions, the constants x_0 and n_0 read from tables, are 3.1133 and 3.74603 respectively. A graph of this Beta prior function used for all launch vehicles is shown below.

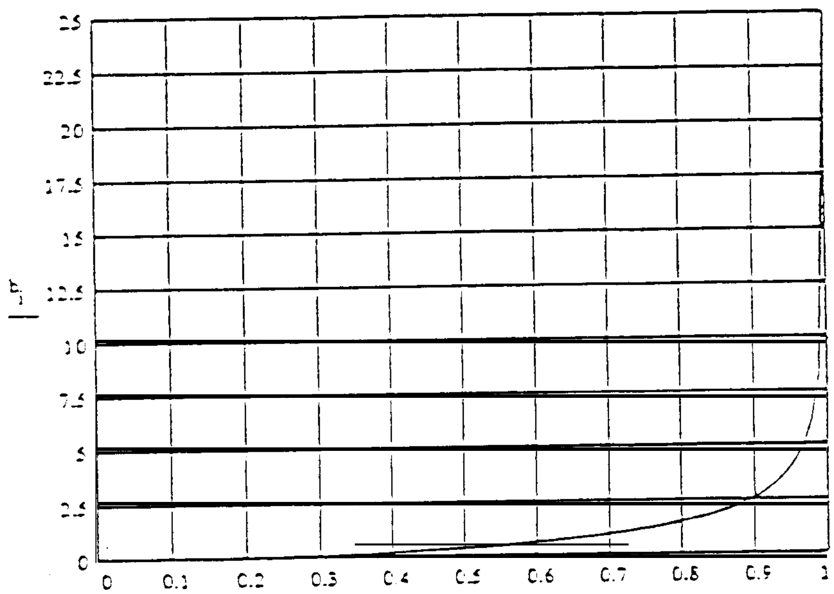


fig 2. Beta prior used in calculations

Calculating the Beta Posterior Function

After the Beta prior was calculated is was relatively simple to create a Beta posterior function. From a given sample of launches the number of launches (n) and the number of successes (x) were tabulated. These values, along with the values for x_0 and n_0 were then put into a Beta function shown below to form the Beta posterior.

$$g_i := \frac{\Gamma(n + no)}{(\Gamma(x + xo)\cdot\Gamma(n + no - x - xo))}\cdot(p_i)^{(x + xo) - 1}\cdot(1 - p_i)^{(n + no - x - xo) - 1}$$

On the following six pages are reliability graphs for several different launch vehicle families. Each graph includes a summary of the equations used so calculate the reliability.

Bayesian Reliability Analysis...ATLAS

For analysis of Atlas, only Atlas/Centaur combinations were counted in the number of launches. These included SLV-3C, SLV-3D, G and Atlas I models with launches after January 1970, with the last counted launch on Jul. 25, 1990.

Number of launches._ $n := 49$ Number successful__ $x := 43$

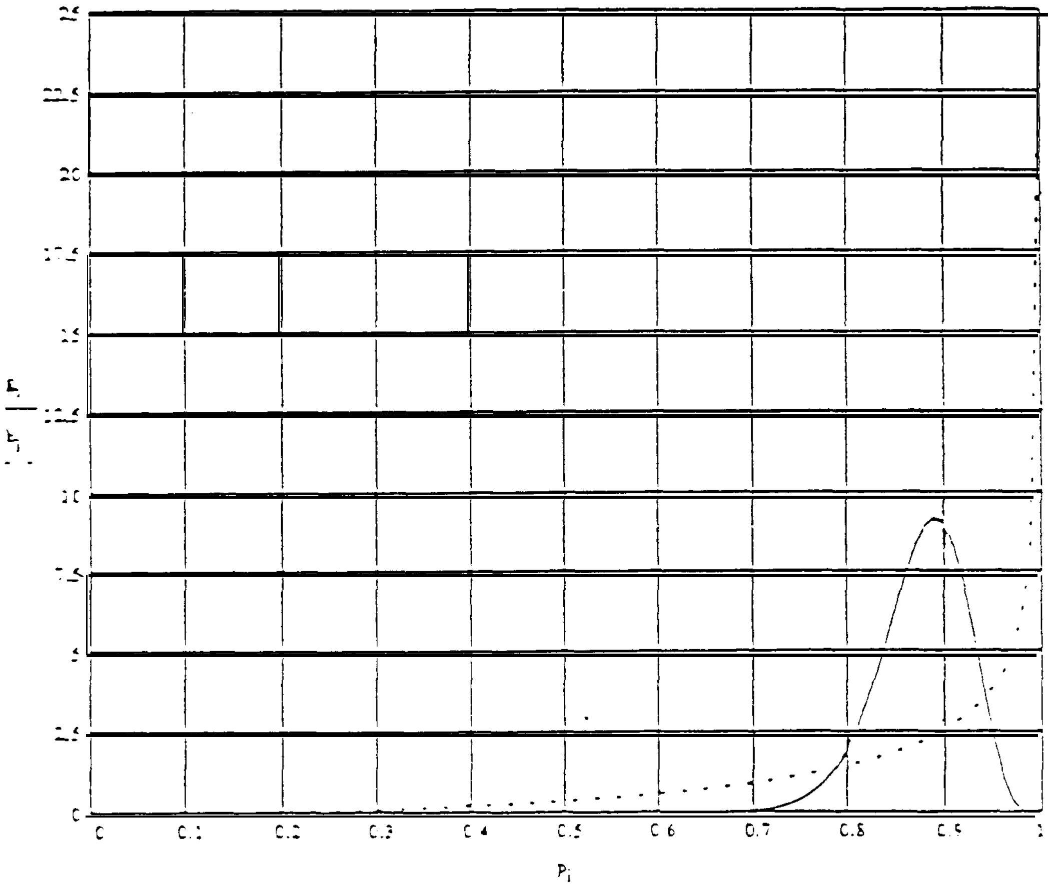
Using a Beta prior distribution with mean of .85 and a 95 % confidence interval bounded by .50 we get...

$$no := 3.74603 \quad xo := 3.1841$$

$$i := 0, 1 .. 100 \quad p_i := \frac{i}{100.1}$$

Beta prior distribution... $$b_i := \frac{\Gamma(no)}{(\Gamma(xo)\cdot\Gamma(no - xo))}\cdot(p_i)^{(xo-1)}\cdot(1-p_i)^{(no-xo-1)}$$

Posterior Distribution... $$g_i := \frac{\Gamma(n+no)}{(\Gamma(x+xo)\cdot\Gamma(n+no-x-xo))}\cdot(p_i)^{(x+xo)-1}\cdot(1-p_i)^{(n+no-x-xo)-1}$$



$$E := \frac{x - xo}{(n + no)} \qquad E = 0.876$$ The predicted reliability is 87.6 %

Bayesian Reliability Analysis... DELTA

For Delta there are a total of 221 launches. The data here represents the last 121 launches. WI of these launches were made with a consistant family begining with a Delta 2914 launch in January, 1974.

Number of launches._ a := 121 Number successful... x:=117

Using a Beta prior distribution with mean of .85 and a 90 % confidence interval bounded by .50 and .95 we get...

$$no := 3.74603 \quad xo := 3.1843$$

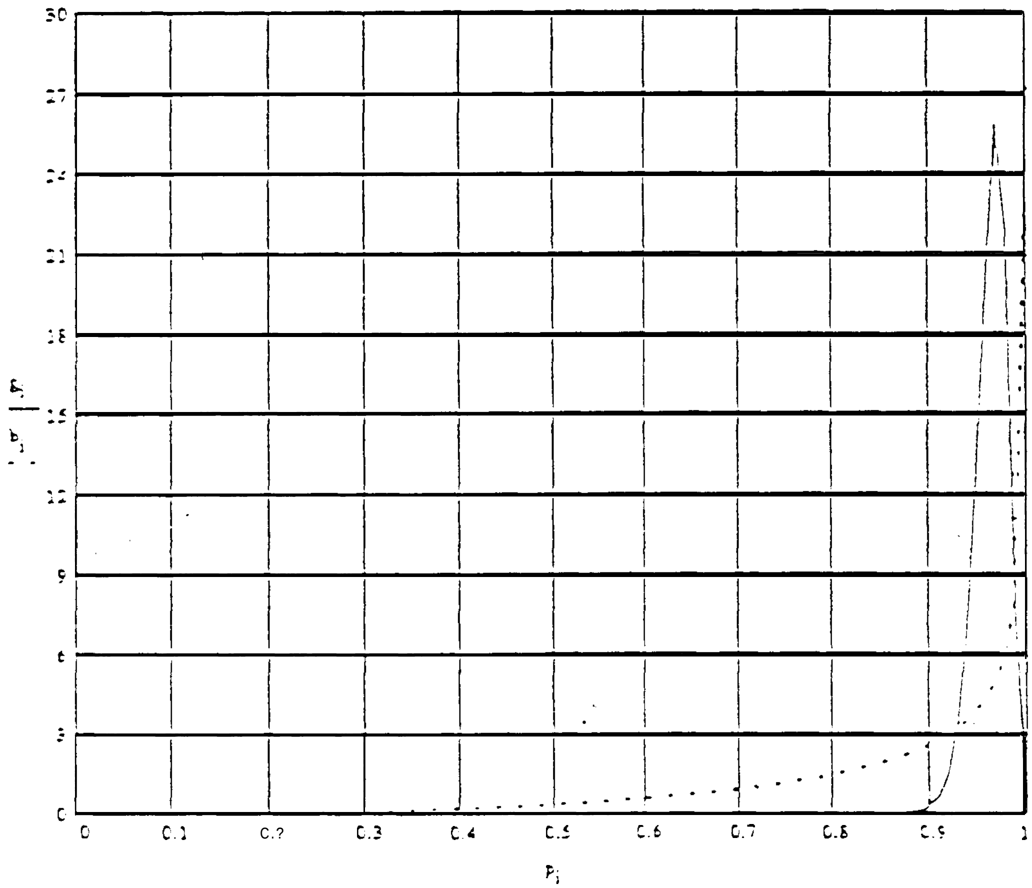
$$i := 0, 1 .. 100 \quad p_i := \frac{i}{100.1}$$

Beta prior, distribution...

$$b_i := \frac{\Gamma(no)}{(\Gamma(xo)\cdot\Gamma(no - xo))}\cdot(p_i)^{(xo-1)}\cdot(1-p_i)^{(no-xo-1)}$$

Posterior Distribution...

$$g_i := \frac{\Gamma(n + no)}{(\Gamma(x + xo)\cdot\Gamma(n + no - x - xo))}\cdot(p_i)^{(x+xo)-1}\cdot(1-p_i)^{(n+no-x-xo)-1}$$



$$E := \frac{x + xo}{(n + no)} \quad E = 0.963$$

The predicted reliability is 96.3 %

Bayesian Reliability Analysis...PEGASUS

The Pegasus ELV has been launched only four times. Out of these four there are two definite successes. Two are sometimes considered failures.

Number of hunches... $n := 4$ Number successful._ $x := 4$

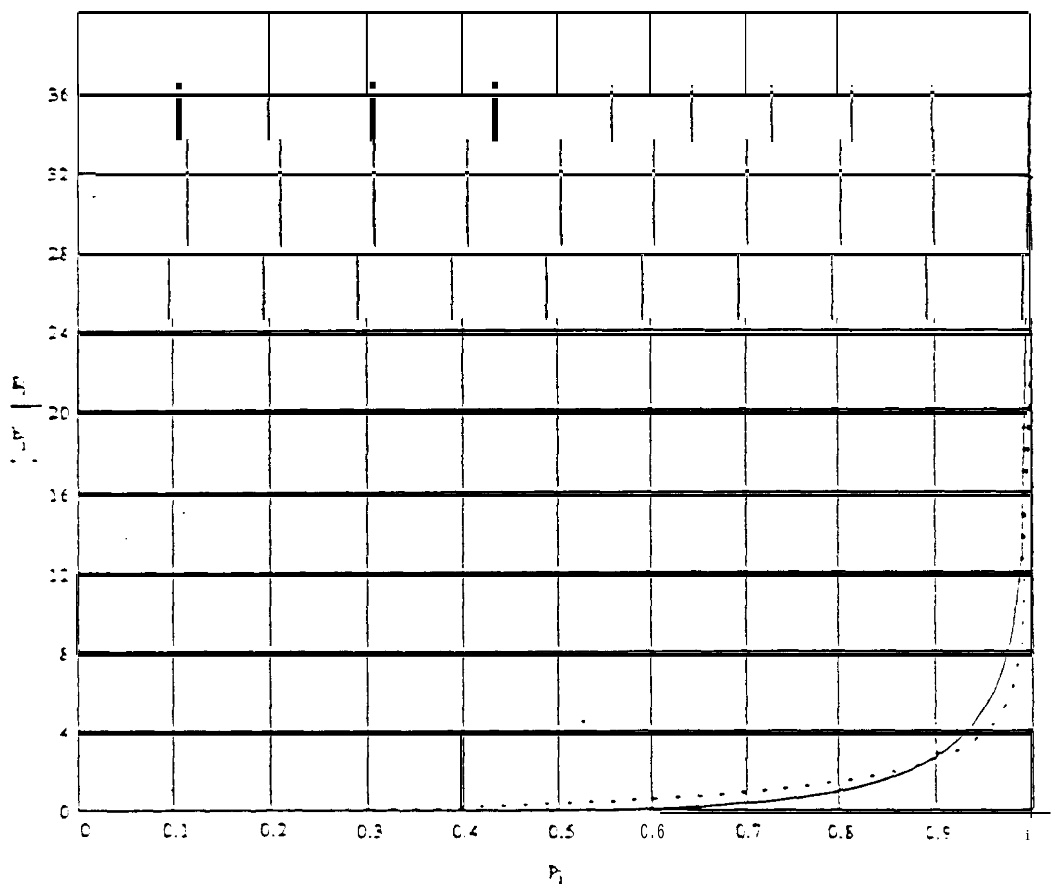
Using a **Beta** prior **distribution** with mean of .85 and a 95 % confidence interval bounded by SO we get...

$$no := 3.74603 \quad x0 := 3.1843$$

$$j := 0, 1 .. 100 \quad p_j := \frac{j}{100.1}$$

Beta prior distribution... $b_i := \frac{\Gamma(no)}{(\Gamma(xo)\cdot\Gamma(no-xo))}\cdot(p_i)^{(xo-1)}\cdot(1-p_i)^{(no-xo-1)}$

Posterior Distribution... $g_i := \frac{\Gamma(n+no)}{(\Gamma(x+xo)\cdot\Gamma(n+no-x-xo))}\cdot(p_i)^{(x+xo)-1}\cdot(1-p_i)^{(n+no-x-xo)-1}$



$E := \frac{x+xo}{(n+no)}$ $E = 0.927$ The predicted reliability is 92.7 %

Bayesian Reliability Analysis...PEGASUS

The Pegasus ELV has been launched only four limes. Out of these four there are two definite successes. Two are sometimes considered failures.

Number of Launches... $n := 4$ Number successful._ $x := 2$

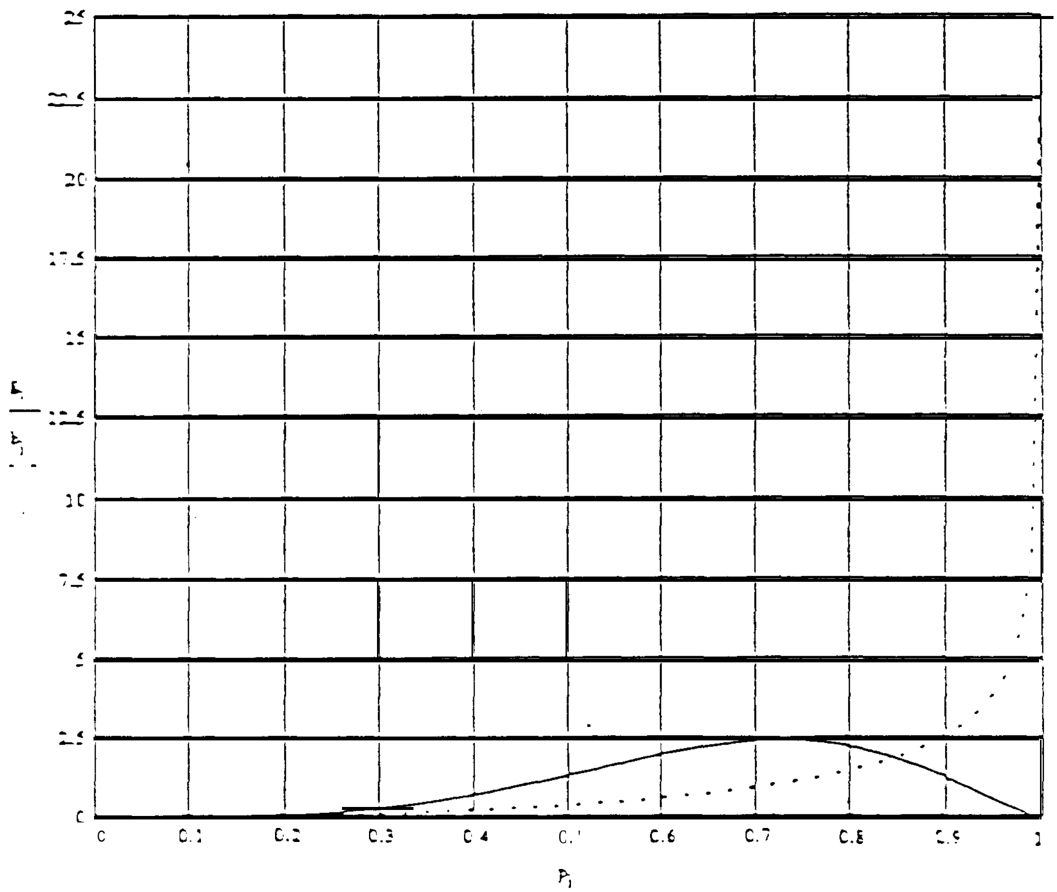
Using a Beta prior distribution with mean of .85 and a 95% confidence interval bound4 by .50 we gel...

$$no := 3.74603 \quad xo := 3.1843$$

$$i := 0, 1 .. 100 \quad p_i := \frac{i}{100.1}$$

Beta prior distribution... $b_i := \frac{\Gamma(no)}{(\Gamma(xo)\cdot\Gamma(no-xo))}\cdot(p_i)^{(xo-1)}\cdot(1-p_i)^{(no-xo-1)}$

Posterior Distribution... $g_i := \frac{\Gamma(n+no)}{(\Gamma(x+xo)\cdot\Gamma(n+no-x-xo))}\cdot(p_i)^{(x+xo)-1}\cdot(1-p_i)^{(n+no-x-xo)-1}$



$$E := \frac{x+xo}{(n+no)}$$ $E = 0.669$ The predicted reliability is 66.9 %

Bayesian Reliability Analysis...TITAN

For analysis of the Titan family the following models were counted as a consistant family: Titan 3C, 3D, 3E, 34D, III, and IV. All launches counted were after January 1970 and the last counted launch was Nov. 12, 1990.

Number of launches... $n := 72$ Number successful... $x := 64$

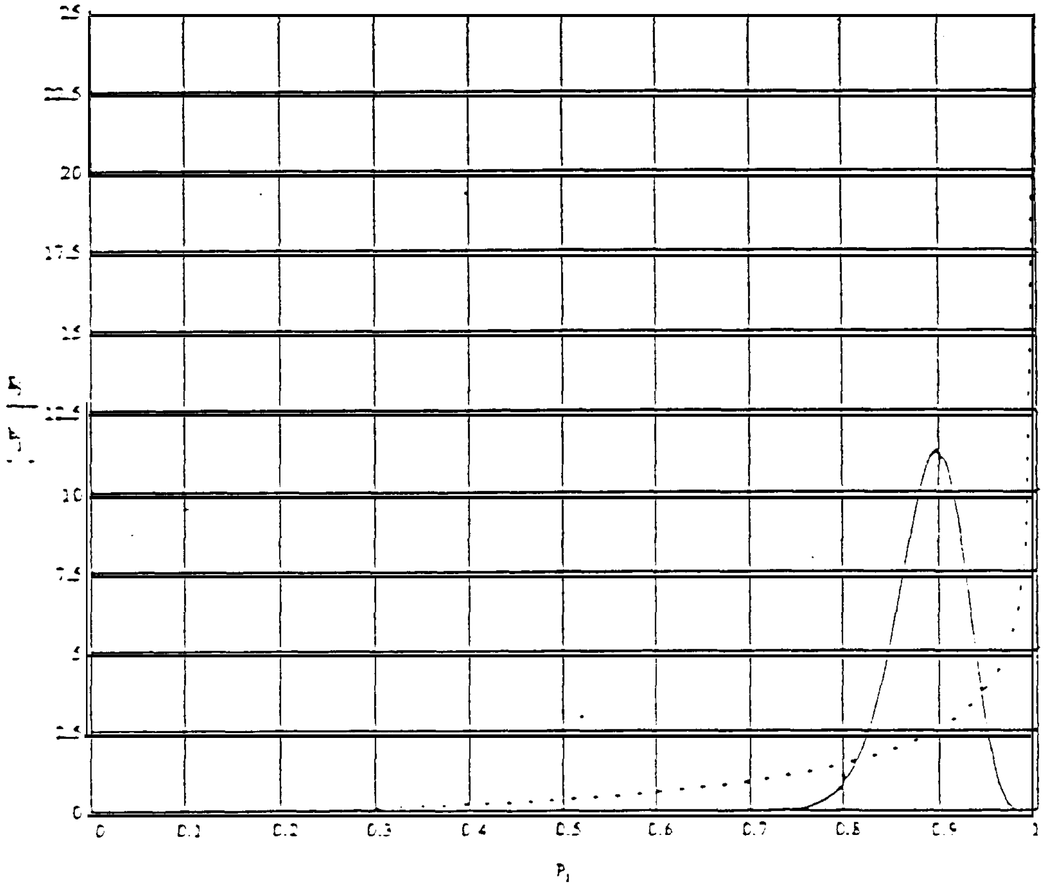
Using a Beta prior distribution with mean of .85 and a 95 % confidence *interval* bounded by .50 we get...

$$no := 3.74603 \quad xo := 3.1843$$

$$i := 0, 1 .. 100 \quad p_i := \frac{i}{100.1}$$

Beta prior distribution... $$b_i := \frac{\Gamma(no)}{(\Gamma(xo)\cdot\Gamma(no - xo))}\cdot(p_i)^{(xo-1)}\cdot(1-p_i)^{(no-xo-1)}$$

Posterior Distribution... $$g_i := \frac{\Gamma(n+no)}{(\Gamma(x+xo)\cdot\Gamma(n+no-X-xo))}\cdot(p_i)^{(x+xo)-1}\cdot(1-p_i)^{(n+no-x-xo)-1}$$



$$E := \frac{x + xo}{(n + no)} \quad E = 0.887$$ The predicted reliability is 88.7 %

APPENDIX B
TIROS RELIABILITY TRENDS

TIROS RELIABILITY TRENDS
(1970 - 1994)

August 30, 1994

This study assesses past reliability of the Television/Infrared Observation Satellites (TIROS) and examines trends which may useful in improving and predicting future TIROS satellite reliability performance.

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In Support Of
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Table 1 – TIROS SATELLITE LIVES

SATELLITE	FAMILY	LAUNCH	EOL	LIFE*	REASON
ITOS-1	TIROS-H	1/23/70	6/19/71	1.40	FAILED, MOTOR
NOAA-1	TIROS-H	12/11/70	8/19/71	0.69	TIME
NOAA-2	TIROS-H	10/15/72	1/30/75	2.29	TIME
NOAA-3	TIROS-M	11/06/73	8/31/76	2.62	TIME
NOAA-4	TIROS-H	11/15/74	11/18/78	4.01	TIME
NOAA-5	TIROS-M	7/29/76	7/16/79	2.92	TIME
TIROS-N	TIROS-N	10/13/78	2/27/81	2.36	FAILED, ADAC
NOAA-6(A)	TIROS-N	6/27/79	3/31/87	4.32	TIME
NOAA-7(C)	TIROS-N	6/23/81	6/07/86	4.95	FAILED, POWER
NOAA-8(E)	ATN	3/26/E?	07/01/84	1.26	FAILED, ADAC
NOAA-9(F)	ATN	12/12/84	2/??/87	2.17	FAILED, MSU
NOAA-10(G)	ATN	9/17/87	ACTIVE	6.71	TIME
NOAA-11(H)	ATN	9/24/88	ACTIVE	5.75	TIME
NOAA-12(D)	TIROS-N	5/14/91	ACTIVE	3.12	TIME
NOAA-13(I)	ATN	8/09/93	8/21/93	0.05	FAILED, POWER
				======	
				44.66	

* LIFE IS MEASURED IN YEARS. FOR SATELLITES STILL ACTIVE LIFE IS MEASURED UP THROUGH THE END OF JUNE 1994.

The third parameter ($t0$) represents an initial period of time when no failures are likely to occur. In other words, the third parameter shifts the origin of the Weibull away from zero. Through iteration, the best correlation occurred with $t0 = -0.8$ years. This implies that the origin of the Weibull curve starts about ten months prior to launch In other words, the spacecraft have experienced the equivalent of ten months of use prior to launch.

Another important consideration in this analysis is that the regression should be performed as Time against Reliability. This is because the Reliability values are known with more certainty since they are a function of the known number of spacecraft_ The Time values, on the other hand, represent best estimates of operating time and thus include some uncertainty. Tne relationship between the regression analysis and the Weibull parameters is:

$$\eta = \text{SCALE} = e^{\text{intercept}}$$
$$\beta = \text{SHAPE} = 1/\text{slope}$$

Table 2 shows the calculation details and results of the median rank regression process Notice that while the calculations only involve the failed spacecraft, the rankings are based on the total number spacecraft. Tne table columns are defined as:

RANK = s/c number (sorted in ascending order by useful life)

t = failure time in years after launch

t-t0 = actual failure time from Weibull origin

ADJ. RANK = rank of failed s/c accounting for truncated s/c
= (((N-Rank+1) * PrevAdjRank) + (N+1)) / (N-Rank+2)
where N = total number of s/c = 15

MED. RANK = median rank as interpolated from a statistical table,
it can also be estimated as (AdjRank-0.3) / (N+0.4)

Ps = 1 - MED. RANK

X = X-values from linearly transformed Weibull equation

Y = Y-values from linearly transformed Weibull equation

Table 2 -- TIROS Median Rank Regression

RANK	t	t-t0	ADJ. RANK	MED. RANK	PS	X ln(-ln Ps)	Y ln(t-t0)
1	0.05	0.88	1.00	0.045	0.954	-3.068	-0.128
2	0.69						
3	1.26	2.09	2.07	0.115	0.885	-2.102	0.737
4	1.40	2.23	3.14	0.185	0.815	-1.589	0.802
5	2.17	3.00	4.21	0.254	0.746	-1.227	1.099
6	2.29						
7	2.38	3.21	5.39	0.331	0.669	-0.911	1.166
8	2.82						
9	2.92						
10	[illegible]						
11	4.01						
12	4.32						
13	4.95	5.78	8.04	0.503	0.497	-0.358	1.754
14	5.75						
15	6.71						

Regression Output:

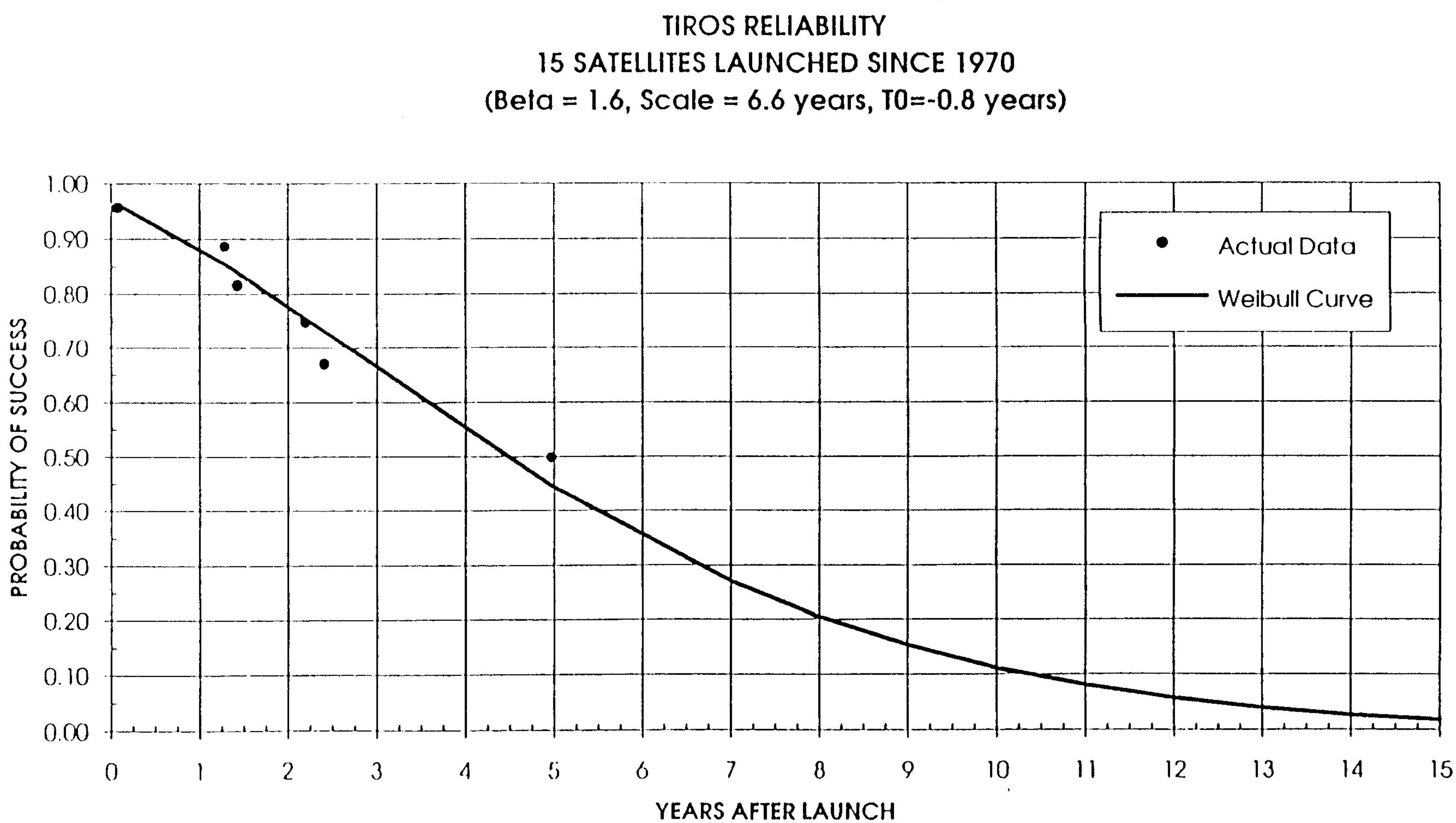
Cons-tarn	1.890 = INTERCEPT
Std Err of Y Estimate	0.112
R Squared	0.962
No. of Observations	6
X Coefficient(s)	0.638 = SLOPE

Therefore: η = Scale = $e^{\text{Intercept}}$ = 6.6 years

β = Shape = 1/Slope = 1.6

The data and the resulting Weibull curve are shown in Figure 1.

FIGURE 1


TIROS RELIABILITY
15 SATELLITES LAUNCHED SINCE 1970
(Beta = 1.6, Scale = 6.6 years, T0=-0.8 years)
Actual Data
Weibull Curve
PROBABILITY OF SUCCESS
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
YEARS AFTER LAUNCH

3.2. TREND ANALYSIS BASED ON LAUNCH DATES. The trend line shown in Figure 2 results from linear regression of the lifetime data regardless of whether the spacecraft failed or was time-truncated. The objective of this analysis is to predict the reliability of future TIROS spacecraft via extrapolation. The trend line shows a positive slope indicating that we are building better spacecraft today than in the past This infers that tomorrow's spacecraft will be even better. However, in addition to the normal cautions of extrapolation, one must note that the correlation between the resulting nend line and the individual data points is very weak

Regression Output:

Constant	2.083 = INTERCEPT
Std Err of Y Estimate	1.017
R Squared	0.073
No. of Observations	15
X Coefficient(s)	0.113 = SLOPE
Std Err of Coef.	0.111

The trend line indicates that the useful Me, measured in years, of a TIROS satellite follows the equation,

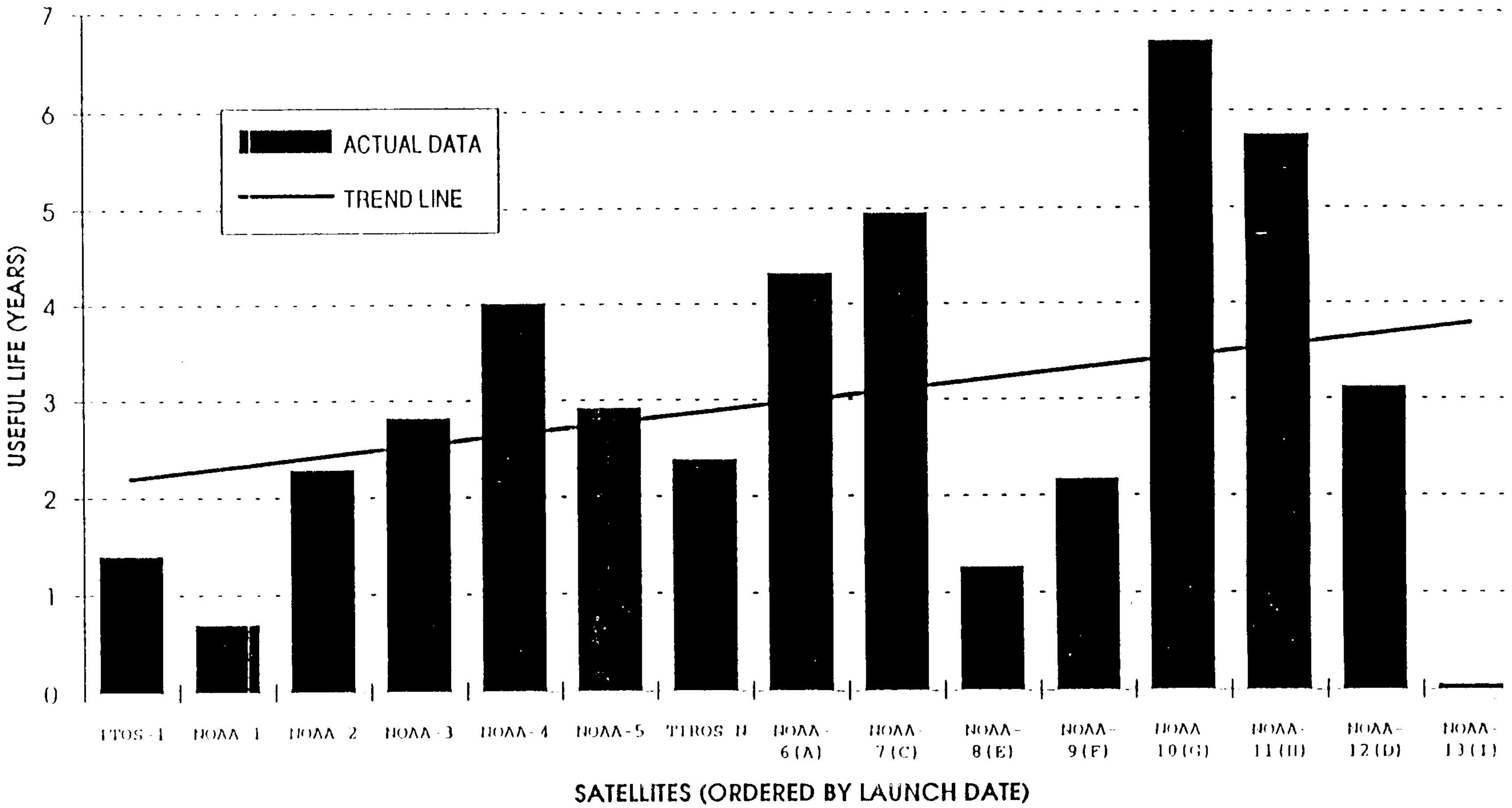
USEFUL LIFE = 0.11 * SATELLITE ORDER + 2.08

where SATELLITE ORDER is the launch sequence number starting with ITOS-1 = 1, NOAA-1 = 2. etc.

The correlation between the trend line and the data is very weak. Note that NOAA-10, -11 and - 12 are still active. Additional operating time on these three satellites will improve the correlation. There appears to be more deviation from the trend line in recent years. This suggests that while we are generally getting more life from our newer satellites, our design and manufacturing processes may be out-of-control. Also, notice that within any one family of satellites, the trend appears to increase more rapidly than for the entire series of 15 TIROS satellites. These families are: TIROS-M (ITOS-1 through NOAA-5), TIROS-N (TIROS-N through NOAA-7 plus NOAA-12), and ATN (NOAA-8 through NOAA-13 less NOAA-12). Further examination of the TIROS data may reveal other reasons for the trends observed.

FIGURE 2

TIROS USEFUL LIVES (1970-1994)



4. OVERALL GSFC EXPERIENCE. Seventy-three GSFC spacecraft launched from the beginning of 1970 to June 30, 1994 were analyzed to determine the best-fit Weibull probability of success function. A Weibull curve was fit to the useful life probability (Ps) and corresponding TIME data of Table 3 using linear regression. The Weibull reliability function,

$$Ps = e^{-(\frac{t}{\eta})^{\beta}}$$

is linearized by taking the double log of both sides of the equation resulting in

$$\ln[-\ln(Ps)] = \beta \ln(TIME) - \beta \ln \eta$$

An important consideration in this analysis is that TIME should be regressed against Ps. This is because the Ps values are known with absolute certainty since they are a function of the known number of spacecraft The Time values, on the other hand, represent best estimates of operating time and thus include some uncertainty. Rearranging the terms of the linearized Weibull function to the classic linear equation form of Y = mX + b yields,

$$\ln(TIME) = 1/\beta * \ln[-\ln(Ps)] + \ln \eta$$

where: η = Weibull Scale parameter = $e^{intercept}$
β = Weibull Shape parameter = 1/slope

The Table 3 shows the calculation details and results of the median rank regression process. Notice that while the calculations only involve the failed spacecraft, the rankings are base3 on the total number spacecraft The table columns are defined as:

SPACECRAFT	= Name of the spacecraft
FAIL?	= Failure indicator. [a one(1) indicates that the s/c failed]
RANK	= s/c number (sorted in ascending order by useful life)
TIME	= failure time in years after launch
ADJ. RANK	= rank of failed **sic accounting** for truncated s/c = (((N-Rank+1) * PrevAdjRank) + (N+1)) / (N-Rank+2) where N = total number of s/c = 73
MED. RANK	= median rank estimated as (AdjRank-0.3) / (N+0.4), it can also be interpolated from a statistical table
Ps	= 1-MED. RANK

X	= X-values from linearly transformed Weibull equation
Y	= Y-values from linearly transformed Weibull equation

Table 3

73 SPACECRAFT LIFETIMES PROBABILITY EVALUATION '70-'94 (6/30/94)

SPACECRAFT	FAIL?	RANK	TIME	ADJ. RANK	MED. RANK	Ps	X = ln(-ln(Ps))	Y = ln (TIME)
NOAA-13 (I)	1	1	0.05	1.0000	0.0095	0.9905	-4.6478	-2.9957
GOES-I		2	0.28	1.0000				
AE-D	1	3	0.42	2.0139	0.0233	0.9767	-3.7454	-0.8675
SAS-B	1	4	0.54	3.0278	0.0372	0.9628	-3.2736	-0.6162
NOAA-1 (ITOS-A)	1	5	0.56	4.0417	0.0510	0.9490	-2.9503	-0.5798
Magsat		6	0.61	4.0417				
SMM	1	7	0.83	5.0705	0.0650	0.9350	-2.7001	-0.1863
PEGSAT		8	0.83	5.0705				
NOAA-8 (E)	1	9	1.25	6.1149	0.0792	0.9208	-2.4945	0.[illegible]231
TIROS-M	1	10	1.4	7.1592	0.0935	0.9065	-2.3217	0.3365
TDRS-6		11	1.46	7.1592				
DE-2 (B)	1	12	1.54	8.2202	0.1079	0.8921	-2.1700	0.4318
GOES-2 (B)	1	13	1.55	9.2812	0.1224	0.8776	-2.0362	0.4383
SMS-1	1	14	1.6	10.3421	0.1368	0.8632	-1.9165	0.4700
SAMPEX		15	2	10.3421				
EUVE		16	2.06	10.3421				
NOAA-9 (F)	1	17	2.17	11.4397	0.1518	0.8482	-1.8042	0.7747
GOES-3 (C)	1	18	2.21	12.5372	0.1667	0.8333	-1.7016	[illegible]930
GOES-4D	1	19	2.21	13.6348	0.1817	0.8183	-1.6070	0.[illegible]930
NOAA-2 (ITOS-D)	1	20	2.25	14.7323	0.1966	0.8034	-1.5190	0.8109
TIROS-N	1	21	2.38	15.8299	0.2116	0.7884	-1.4367	[illegible]
AEM-A (HCMM)	1	22	2.4	16.9274	0.2265	0.7735	-1.3592	0.8[illegible]
AEM-B (SAGE)	1	23	2.75	18.0250	0.2415	0.7585	-1.2859	1.011[illegible]
UARS		24	2.79	18.0250				
NOAA-3 (ITOS-F)	1	25	2.84	19.1445	0.2567	0.7433	-1.2150	1.0438
SSS-A		26	2.87	19.1445				
TDRS-5		27	2.92	19.1445				
NOAA-5 (ITOS-H)	1	28	2.96	20.3116	0.2726	0.7274	-1.1447	[illegible]085[illegible]

SPACECRAFT	FAIL?	RANK	TIME	ADJ. RANK	MED. RANK	Ps	X = ln(-ln(Ps))	Y = ln (TIME)
NOAA-12 (D)		29	3.13	20.3116				
OSO-VII		30	3.17	20.3116				
*GOES 5-E	1	31	3.19	21.5318	0.2893	0.7107	-1.0746	1.1600
GRO		32	3.23	21.5318				
OSO-8 (I)		33	3.4	21.5318				
IMP-I		34	3.56	21.5318				
NOAA-7 (C)	1	35	3.62	22.8435	0.3071	0.6929	-1.0026	1.2865
RAE-B		36	3.75	22.8435				
SAS-A	1	37	4	24.1897	0.3255	0.6745	-0.9321	1.3863
NOAA-4 (ITOS-G)	1	38	4	25.5360	0.3438	0.6562	-0.8644	1.3863
HST		39	4.18	25.5360				
COBE		40	4.27	25.5360				
SAS-C ..		41	4.92	25.5360				
AMPTE/CCE		42	4.92	25.5360				
AE-C		43	5	25.5360				
Landsat-C	1	44	5.07	27.0993	0.3651	0.6349	-0.7890	1.6233
ATS-6		45	5.17	27.0993				
TDRS-4 (D)		46	5.3	27.0993				
SMM (Post Repair)		47	5.53	27.0993				
AE-E		48	5.56	27.0993				
Landsat-1 (ERTS-A)		49	5.58	27.0993				
GOES 6 (F)	1	50	5.73	28.9753	0.3907	0.6093	-0.7024	1.7457
TDRS-3 (C)		51	5.75	28.9753				
NOAA-11 (H)		52	5.76	28.9753				
IMP-H	1	53	6.1	31.0219	0.4186	0.5814	-0.6120	1.8083
SMS-2 (B)	1	54	6.5	33.0685	0.4464	0.5536	-0.5253	1.8718
NOAA-10 (G)		55	6.71	33.0685				
Nimbus-6 (F)	1	56	7.18	135.2228	0.4758	0.5242	-0.4372	1.9713
GOES-7 (H)		57	7.34	35.2228				
NOAA-6 (A)		58	7.39	35.2228				
OAC -i		59	8.5	35.2228				
Landsat 2	i	60	8.51	37.8079	0.5110	0.4890	-0.3349	2.1412
GOES-1 (A)	1	61	9.3	40.3931	0.5462	0.4538	-0.2355	2.2300
DE-1(A)		62	9.57	40.3931				

SPACECRAFT	FAIL?	RANK	TIME	ADJ. RANK	MED. RANK	Ps	X = ln(-ln(Ps))	Y = ln (TIME)
ERBS		63	9.74	40.3931				
ISEE-A		64	9.93	40.3931				
Nimbus-IV		65	10	40.3931				
Nimbus-5	1	66	10.3	44.1272	0.5971	0.4029	-0.0953	2.3321
Landsat-5 (D)		67	10.33	44.1272				
TDRS-1 (A)		68	11.24	44.1272				
Landsat-4 (D)		69	11.96	44.1272				
Nimbus-7 (G)	1	70	14.5	50.1017	0.6785	0.3215	0.1264	2.6741
ISEE-C		71	15.9	50.1017				
IUE		72	16.44	50.1017				
IMP VIII(J)		73	20.7	50.1017				

Regression Output:

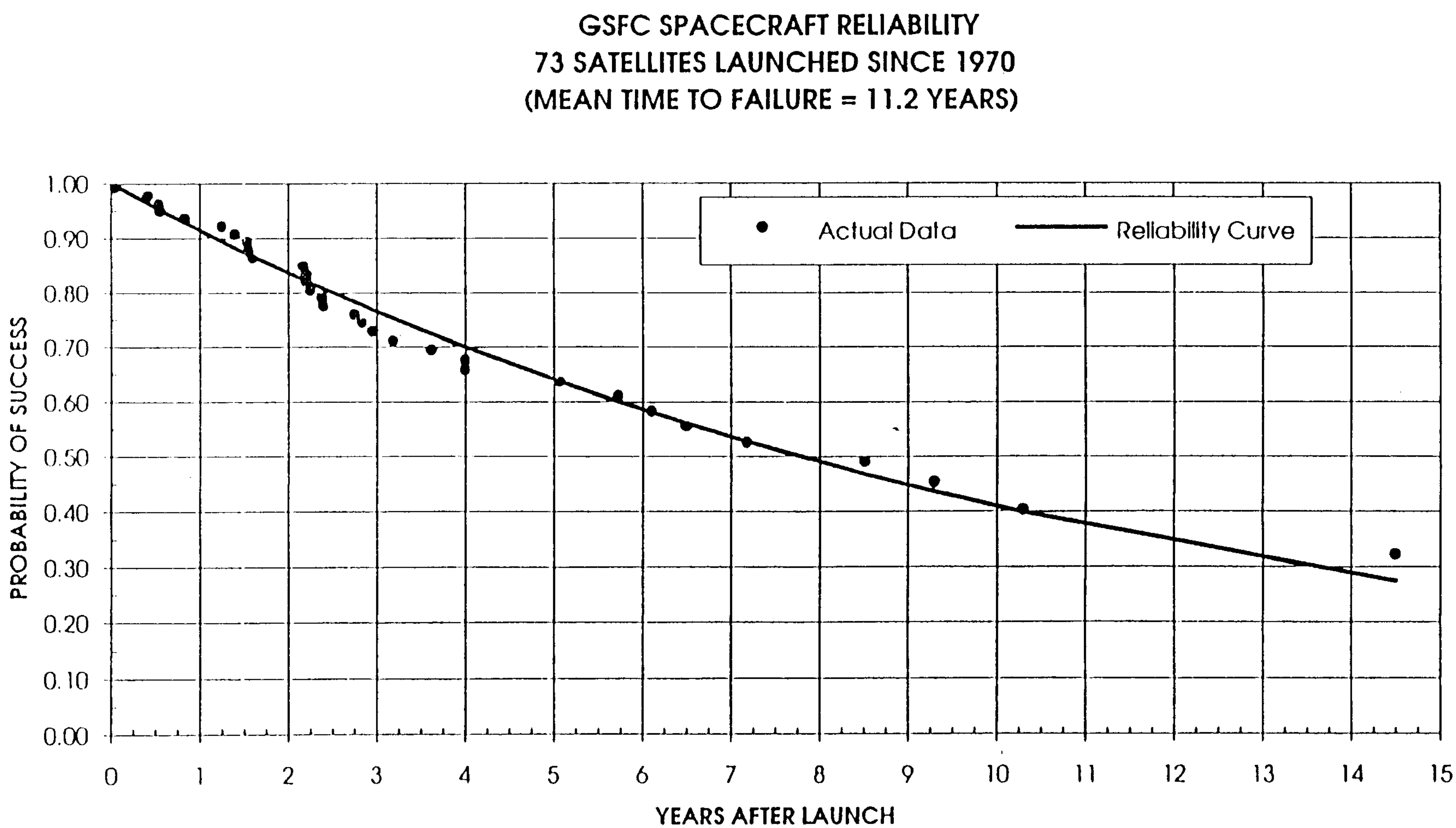
Constant	2.413 = Intercept
Std Err of Y Estimate	0.064
R Squared	0.966
No. of Observations	32
X Coefficient(s)	1.002 = Slope
Std Err of Coef.	0.034

Shape parameter(β) = 1.00

Scale parameter (η) = 11.2 years

With a shape parameter of unity, this Weibull distribution is equivalent to an exponential distribution having a Mean Time To Failure (MTTF) of 11.2 years. Figure 3 shows the data and the derived reliability curve.

Figure 3


GSFC SPACECRAFT RELIABILITY
73 SATELLITES LAUNCHED SINCE 1970
(MEAN TIME TO FAILURE = 11.2 YEARS)
Actual Data
Reliability Curve
PROBABILITY OF SUCCESS
YEARS AFTER LAUNCH
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

5. DISCUSSION. The TIROS-derived Weibull shape parameter (1.6) is greater than the 1.0 derived from Goddard Space Flight Center's (GSFC) entire base of experience. This implies that the TIROS satellites degrade more rapidly than a typical GSFC satellite. The TIROS-derived Weibull scale parameter (6.6 years) is less than the 11.2 years derived from the GSFC experience base. Additionally, the TIROS data analysis fit a three-parameter Weibull function best with t0 = -0.8 years. These differences implies that TIROS satellites are less reliable than typical GSFC satellites. However, these conclusion may be misleading since more of the TIROS satellites were time terminated than in the GSFC experience base. The relatively small number of TIROS satellites makes the TIROS analysis more sensitive, than the overall GSFC analysis, to any one data point Further examination of the TIROS data may reveal other reasons for this difference in shape parameters.